LAKE OKEECHOBEE REGULATION SCHEDULE STUDY

Simulation of Alternative Operational Schedules for Lake Okeechobee,
Final Report – Appendix A
Water Quality Modeling Results – Appendix B
WSE Implementation Plan – Appendix C

June 1999

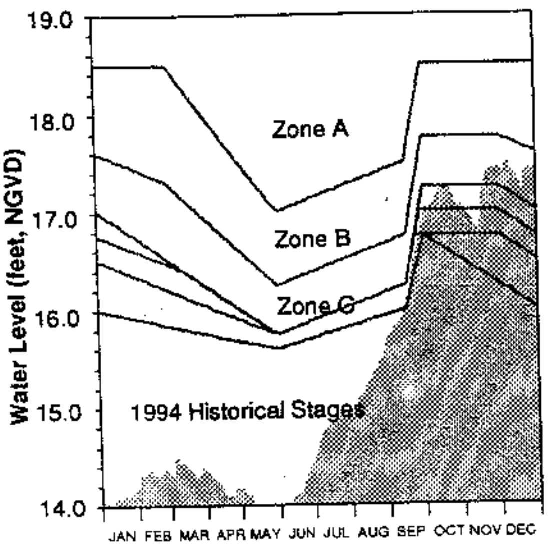
APPENDIX A

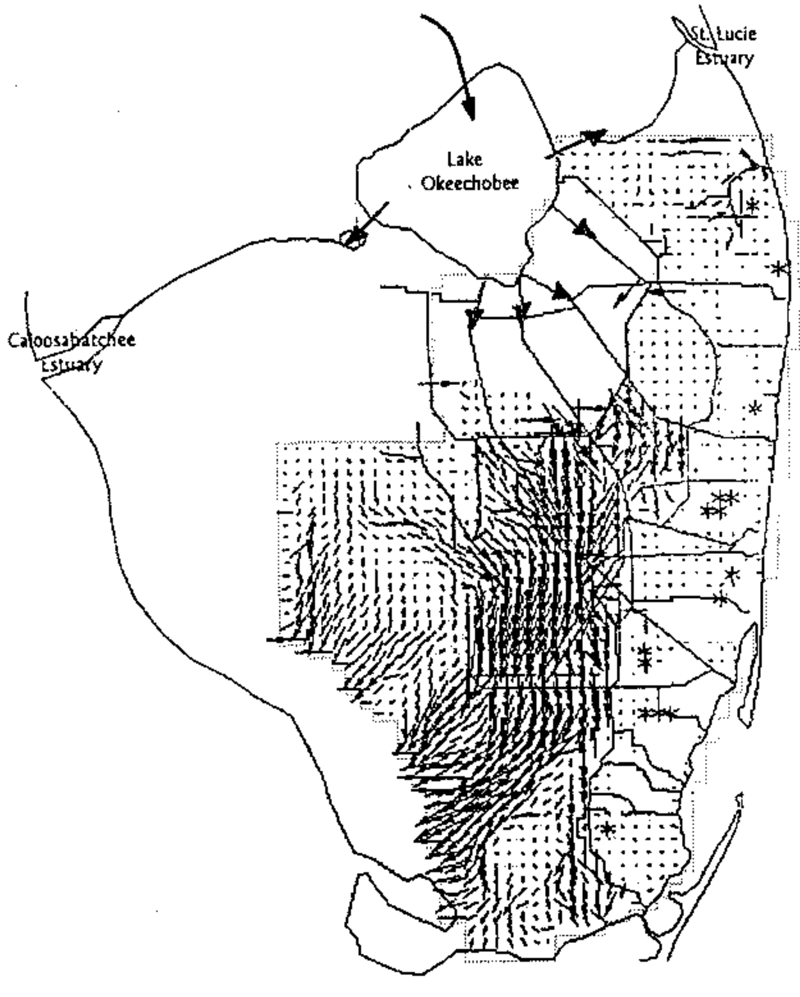
SIMULATION of ALTERNATIVE OPERATIONAL SCHEDULES for LAKE OKEECHOBEE FINAL REPORT

FINAL REPORT

Simulation of Alternative Operational Schedules for Lake Okeechobee

Prepared in Support of the Lake Okeechobee Regulation Schedule Study





Calvin J. Neidrauer, Paul J. Trimble, Everett R. Santee

Hydrologic Systems Modeling Division, Planning Department

SOUTH FLORIDA WATER MANAGEMENT DISTRICT

West Palm Beach, Florida May 7, 1998

MEMORANDUM

TO: Barry Rosen, Ph.D., Senior Supervising Environmental Scientist
Upper District Planning Division, Planning Department

THROUGH: Jayantha Obeysekera, Ph.D., P.E., Director, Obey
Hydrologic Systems Modeling Division, Planning Department

FROM: Cal Neidrauer, P.E., Senior Supervising Engineer, HSM, PD CN
Paul Trimble, Senior Engineer, HSM, PD PT
Ray Santee, Lead Engineer, HSM, PD RS

DATE: May 7, 1998

SUBJECT: Simulation of Alternative Operational Schedules for Lake Okeechobee

In support of the Lake Okeechobee Regulation Schedule Study (LORSS), simulations of the hydrologic performance of five alternative operational (regulation) schedules have been completed and the attached final report is submitted to further assist the study. This report supersedes the April 30, 1997 draft of the same title. The final report includes the simulation results of the recently developed schedule named WSE; and it also addresses many of the relevant suggestions made in the September 24, 1997 Planning Aid Letter from the U.S. Fish and Wildlife Service and the Florida Game and Freshwater Fish Commission.

This report is intended to summarize and present the hydrologic simulation results and findings of our analysis. Other efforts, not documented in this report, have been, or will be, performed which address performance of the alternative schedules from water quality, ecological, and economic perspectives. It is expected that the synthesis of the findings of these multiple analyses will be prepared by the U.S. Army Corps of Engineers (USACE) as part of the LORSS.

Our report is intended to provide a technical focal point for further analyses by staff from the USACE, SFWMD, and the other agencies participating in the LORSS. The report is not intended to replace USACE documents that are to be prepared for the LORSS, but rather to serve as a technical report to be referenced by USACE documents prepared for the study.

If you have any questions, please give me a call at 687-6506.

CN/cn:

cc:
Dan Cary, PLD
Bob Hamrick, PLD
Karl Havens, ERD
George Hwa, OMD
Ron Mierau, OMD
Kent Loftin, EXO
Dean Powell, PLD
Al Steinman, ERD
Ray Santee, HSM
Geoff Shaughnessy, OMD
Tom Strowd, OMD
Eric Swartz, OMD
Dave Swift, PLD
Paul Trimble, HSM
Tom Teets, LECPD
Randy Van Zee, HSMD
Carl Woehlcke, LECPD

Simulation of Alternative Operational Schedules for Lake Okeechobee

Prepared in Support of the
Lake Okeechobee Regulation Schedule Study

Calvin J. Neidrauer, Paul J. Trimble, Everett R. Santee
Hydrologic Systems Modeling Division, Planning Department
South Florida Water Management District

May 7, 1998

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1. INTRODUCTION

Purpose and Scope of this Report

In support of the Lake Okeechobee Regulation Schedule Study (LORSS), the system-wide effectiveness of five Lake Okeechobee operational (regulation) schedules was simulated with the South Florida Water Management Model. The major assumptions and results of this effort are presented in this report to provide other study team members with information for further analysis. Also included in this report is a precursory evaluation of the trade-offs between the competing objectives for managing the Lake. This analysis is offered as an example of a trade-off methodology that could be applied to assist decision-makers in selecting a preferred operational schedule.

Please note that this report is limited to assessing effects on system-wide hydrology and water supply. All the measures of performance presented in this report are based on the simulation of hydrologic variables. These hydrologically-based performance indicators, or performance measures, are useful surrogates for ecosystem benefits and impacts; however it is expected that further evaluation of the results from water quality, ecological, and economic perspectives will be performed by others as part of the LORSS. It is also expected that the synthesis of the findings of these multiple analysis will be prepared by the U.S. Army Corps of Engineers (USACE). This report is not intended to replace USACE documents that are to be prepared for the LORSS, but rather to serve as a technical report to be referenced by USACE documents.

Background

Lake Okeechobee is the second largest freshwater lake lying wholly within the boundaries of the United States. The Lake benefits south Florida by storing enormous volumes of water during wet periods for subsequent environmental, urban and agricultural needs during dry periods. However, extended periods of high water levels within the Lake have been identified as causing stress to the Lake littoral zone. In addition, south Florida's potential for heavy rains and severe tropical storms requires that water levels in the lake be carefully monitored to ensure that they do not rise to levels that would threaten the structural integrity of the levee system surrounding the Lake. Therefore, when water levels in the lake reach certain elevations designated by the regulation schedule, discharges are made through the major outlets to control excessive buildup of water in the Lake. The timing and magnitude of these releases is not only important for preserving the flood protection of the region, but also for protecting the natural habitats of downstream estuaries and the Everglades.

The multiple, and sometimes competing, objectives associated with managing the lake water levels are:

1. Provide adequate flood protection for the regions surrounding the Lake.
2. Meet the water use requirements of the agricultural and urban areas that are dependent on Lake okeechobee for water supply.

3. Preserve the biological integrity of the estuaries downstream of the Lake's two major outlets to tide.
4. Supply water to the remnant Everglades to restore natural hydroperiods.
5. Preserve and enhance the lake's littoral zone which provides a natural habitat for fish and wildlife.
6. Meet the recreational needs of south Florida.
7. Navigation.

2. OVERVIEW OF THE SCHEDULES EVALUATED

This report presents the hydrologic simulation results and an evaluation of the hydrologic performance of five operational schedules designed to address the competing objectives of managing Lake Okeechobee water levels and outflows. The first four of these schedules include:
(A) the current interim operational schedule (aka Run25);
(B) a schedule originally proposed by the Lake Okeechobee Littoral Zone Technical Group (LOLZTG, 1988), and later refined (aka Run22AZE);
(C) a schedule proposed by the United States Army Corps of Engineers (USACE) for the LORSS (designated as COE); and
(D) a schedule proposed by the South Florida Water Management District's Hydrologic Systems Modeling Division (designated as HSM). The SFWMD-proposed schedule also recommends that the application of recent advances in the field of climatology be applied for increasing the flexibility and efficiency of managing of the Lake water levels and discharges.
(E) The fifth schedule (designated as WSE), was recently developed by the SFWMD's Hydrologic Systems Modeling Division to better balance the competing objectives for managing the Lake; this schedule integrates the concepts introduced in the first four schedules.

<u>A. Operational Schedule 25 (**R25**)</u>
Operational Schedule 25, or Run25, is the current operational schedule for Lake Okeechobee. This schedule was designed specifically for the purpose of minimizing the impacts of large freshwater emergency discharges that are, at times, required for flood protection. The development of this schedule was the result of a comprehensive analysis of a full spectrum of operational rules and schedules completed by the SFWMD (Trimble and Marban, 1988). This schedule appears in Figure 1 and is denoted as R25 on the performance measure graphics. R25 was implemented in 1992 for a 2-year trial period. In 1994, the USACE extended the implementation of R25. R25 was implemented as an interim schedule with the foundation that:

1. It was a more desirable schedule for the estuary ecosystems than the previous operational schedule; This was accomplished by limiting the buildup of water levels during the dry seasons and discharging the required releases to the estuary ecosystem via pulse releases that more resemble an inflow hydrograph resulting from a rainfall event;

2. It did not impact other objectives of managing Lake Okeechobee water levels and discharges. In fact there was overall improvement in performance with this schedule.

At the time of adoption of this schedule, it was recognized that trade-offs existed between the objective of managing the Lake water levels for the health of the littoral zone ecosystems and the objective of managing the Lake for increased water supply capability.

B. Operational Schedule 22AZE (**R22**)

The desire for managing lower stages in Lake Okeechobee led to the development of Operational Schedule 22AZE (aka Run22AZE). The predecessor to Run22AZE, Run22 (Trimble and Marban, 1988), was recommended by the LOLZTG (1988) as the most desirable schedule for the Lake littoral zone ecosystem. Run22AZE was later developed as an improvement to Run22. The Run22AZE schedule appears in Figure 2 and is denoted as R22 in the performance measure graphics. It's design includes:

1. Desirable features of R25 for minimizing impacts to the estuaries;

2. The proposal of the concept of an additional zone to the regulation schedule at lower stages in which releases were made only to southward to the Everglades;

3. An allowance for a large jump in the schedule at the beginning of the wet season. This allows for the capture of large regional rainfall events, which frequently occur in Florida in the month of June, for potential water use during the following dry season.

C. USACE Proposed Operational Schedule (**COE**)

The USACE operational schedule is very similar to Run25, but includes the lower zone introduced by Run22AZE. This schedule is shown in Figure 3 and is denoted as COE_REC or COE on the performance measure graphics. The features of this schedule include:

1. An allowance for a potential increase in storage over Run22AZE immediately after the peak of the hurricane season;

2. Discharges to the Everglades in the lowest zone of the schedule are discontinued at a higher water elevation except during June and July.

D. SFWMD Proposed Operational Schedule (**HSM**)

The SFWMD proposal was developed by the authors of this report as part of the Lower East Coast Water Supply Plan. This schedule appears in Figure 4 and is denoted as HSM_REC or HSM on the performance measure graphics. This operational schedule offers guidelines for adjusting water releases from Lake Okeechobee for each zone based, in part, on a six-month Lake Okeechobee inflow forecast. The methodology for the forecast is described in a separate detailed report (Trimble, Santee and Neidrauer; 1998), and the forecast is computed based on climate indices made regularly available by the National Oceanographic and Atmospheric Association (NOAA).

The suggested classification of Lake Okeechobee inflows for each climate condition are listed in Table 1. Table 3 presents other important operational guidelines for the use of schedule HSM.

Table 1. Climate-Hydrology Classification for Schedule HSM

Condition	Dry	Dry to Normal	Normal to Wet	Wet	Very Wet
6-Month Lake Inflow Forecast (Million Acre-feet)	0.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	>3.0

The HSM schedule also introduces the same new lower zone as the other proposed schedules for which water releases are made only southward to the Everglades. However, this schedule makes southward releases only when the Everglades "needs" the water (for the purpose of this analysis the "need" was considered to be when average water levels within each Water Conservation Area were below their respective flood release zones). Water needs of the Everglades were always pumped (either via S-7 & S-8 in the 1990 condition, or via the STAs in the 2010 condition). This proposed schedule also recommends pumping releases to the Everglades when Lake water levels are within Zone B in order to reduce the chances for having to make maximum releases to the estuaries.

In summary, the special features of this schedule include:

1. Flexible operations within each operational zone to improve on water management efficiency in meeting the objectives of managing the lake water levels. This can be best accomplished considering climate indices that are easily accessible by NOAA;

2. Inclusion of a new lower zone for releasing water to the Everglades. However, this proposal differs from the other schedules in two ways:
    a. water is only delivered south in this new zone when the Everglades is defined as needing the water;
    b. pulse releases to the estuaries are allowed under very wet conditions when the water is not needed for Everglades hydroperiod enhancement;

3. Everglades water needs are always pumped;

4. Zone B releases to the Everglades WCAs are pumped to avoid the potential for Zone A maximum releases through the Estuaries.

5. During the dry season, releases from the Lake to tide for each zone are assumed to gradually increase up to the maximum recommended discharge for the zone at the top of the zone. Steady flows in Zone C releases are assumed to be initiated at an average magnitude of a Level 3 pulse. This is equivalent to 3000 cfs at S-77 and 1170 cfs at S-80. Zone A releases are increased from Zone B levels to maximum within the first quarter of a foot of Zone A.

E. SFWMD Proposed Operational Schedule (**WSE**)

The purpose of the WSE (**W**ater **S**upply and **E**nvironmental) schedule is to integrate the most desirable features of the first four schedules to develop a schedule which best balances the competing objectives for managing the Lake. This consolidated operational schedule is illustrated in Figure 5. During the dry season (November through May), the delineation of the lower limit of Zone D was based on Operational Schedule 22AZE. Other rules are based on those for Operational Schedule HSM, except for the climate-hydrology classification that is defined in Table 2. Other important operational guidelines for the use of schedule WSE are presented in Table 3.

Table 2. Climate-Hydrology Classification for Schedule WSE

Condition	Dry	Normal	Wet	Very Wet
6-Month Lake Inflow Forecast (Million Acre-feet)	0-1.5	1.5-2.0	2.0-2.5	>2.5

Schedule WSE was developed after it became evident to the developers of the HSM schedule that the best features of the first four schedules could be combined to derive a new schedule which could better achieve a desired balance among the competing objectives for managing the Lake. Input from several public meetings for the LORSS in the spring of 1998, and the September 24, 1997 Planning Aid Letter from the U.S. Fish and Wildlife Service and the Florida Game and Freshwater Fish Commission, provided additional information which helped, in part, the development of schedule WSE.

Table 3. Other Important Lake Regulation Guidelines (Schedules HSM and WSE)

Zone A i) During the wet season (June through October) Zone A discharges are initiated promptly as the Lake water level enters this Zone.
ii) During the dry season (November through May) discharges are only increased to the rate necessary to lower water levels back to Zone B within a reasonable time frame.
iii) Regulatory discharges to the WCAs should be pumped at S-7 and S-8.
Zone B i) During wet season when S-65E flows exceed 7500 cfs revert to wet condition regulatory discharge mode. Continue this mode until S-65E flows decline to less than 1000 cfs, or when water levels fall to Zone C.
ii) During the dry season when S-65E flows exceed 5000 cfs revert to wet condition regulatory discharge mode. Continue until S-65E declines to less than 1000 cfs.
iii) Regulatory discharges to the WCAs should be pumped at S-7 and S-8.
iv) Discharges may be up to maximum capacity as necessary to prevent water levels from exceeding 18.5 ft, NGVD, for prolonged periods.
Zone C i) During wet season when S-65E flows exceed 10000 cfs, revert to wet condition regulatory discharge mode. Continue this mode until S-65E flows decline to less than 2000 cfs, or when water levels fall to Zone D.
ii) During the dry season when S-65E flows exceed 7500 cfs revert to wet condition regulatory discharge mode. Continue until S-65E declines to less than 2000 cfs.
iii) Regulatory discharges to the WCAs are by gravity at S-7 and S-8.
iv) Pumped flow to WCAs when needed for Everglades hydroperiod enhancement. This is normally desirable when the WCAs are below their respective schedules.
Zone D Pumped flow to WCAs when needed for Everglades hydroperiod enhancement. This is normally desirable when the WCAs are below their respective schedules.
Water Conservation Areas Discontinue regulatory releases from Lake to WCAs when the WCA levels rise more than 0.25 feet above the maximum of their upper respective flood regulation schedules.

General Comments on the use of Climate Forecasts for Lake Regulation

Table 2 is unique to schedule WSE, but Table 3 is common to both schedules HSM and WSE. Note from Table 3 that there is a feature which is designed to allow local inflow conditions at S-65E to override the use of the climate forecast. This feature ensures that the flood protection criteria will be adequately satisfied even in the case of an underestimated inflow forecast.

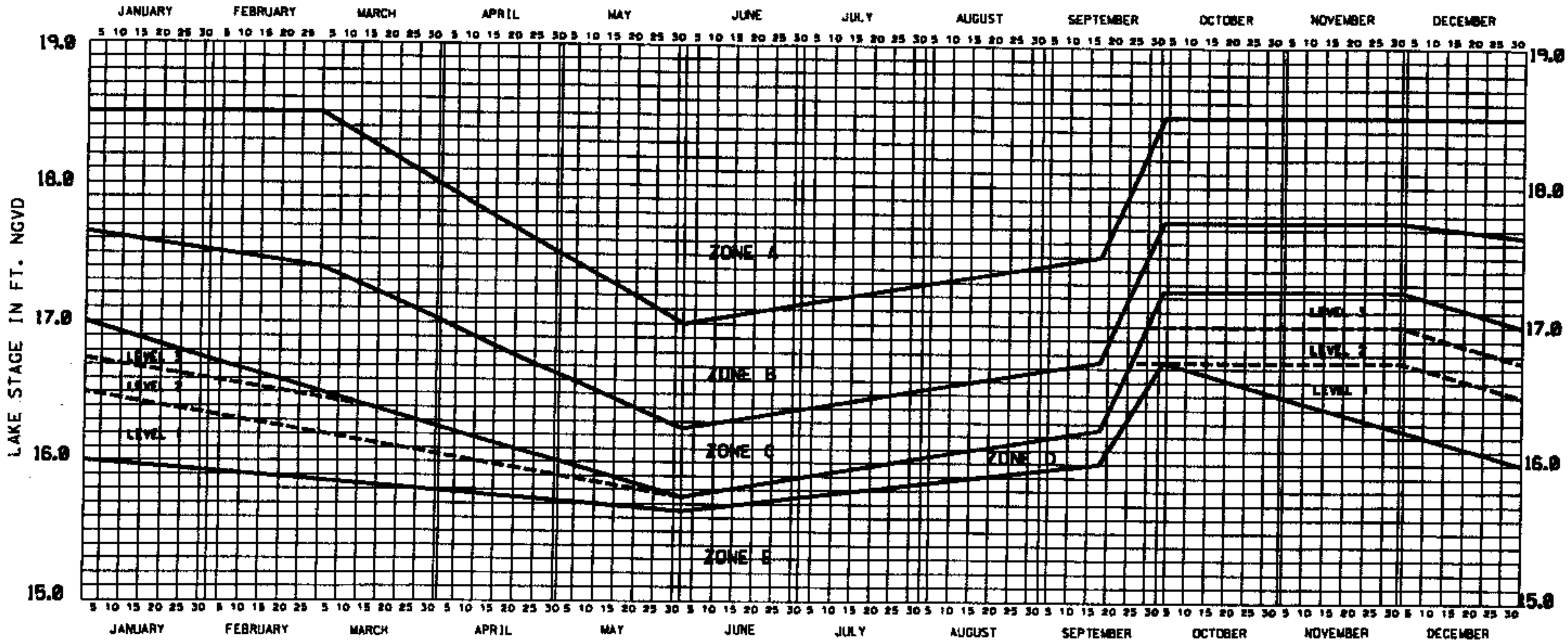
This feature also recognizes, in part, that real-time Lake Okeechobee operations must consider supplemental information, including information which are generally not explicitly stated in operational schedules or in guidelines. Lake operators have traditionally considered input from meteorologists, biologists, hydrologists and engineers, et.al., in making real-time release decisions. Modifying discharges based on weather and/or climate forecasts is not a new concept and was specifically stated as part of the operational rules on many of the historical (e.g., 1956, 1958, 1965, 1970, et. al.) regulation schedules.

The WSE and HSM schedules were both designed to increase operational flexibility. Considering the dynamic shifting of priorities for managing the Lake, it appears desirable to design flexible operating rules that give water managers some latitude to utilize best available multi-disciplinary information, and adjust operations as necessary to achieve a better balance of the competing objectives. Considering the potential benefits from recent lake inflow forecasting tools, and the rapid increase in the state-of-the art in forecasting technology, it makes good sense to establish more flexible rules which allow lake managers to utilize supplementary information and apply their sound judgement in making operational decisions.

A general description of the type of methodology that may be used for the Lake inflow forecast is described in three research papers (Trimble, et al) which are included in Appendix A. In addition to the climate indices used in two of these studies, another index was introduced to represent the state of the Atlantic Ocean thermohaline current. The inclusion of this index was based on discussions with Dr. Christopher Landsea of the Hurricane Research Division of NOAA. This modification further improved the Lake inflow forecasts.

Ongoing research at the SFWMD, and collaboration with international experts in the field, continues to produce improved forecasts. And as the Lake inflow forecasts improve, it is expected that the proficiency of water management will increase even further.

Figure 1. Current Operational Schedule for Lake Okeechobee (R25)



RELEASE THROUGH OUTLETS AS INDICATED

ZONE	AGRICULTURAL CANALS (2)	CALOOSAHATCHEE RIVER (2)	ST. LUCIE CANAL
A	PUMP MAXIMUM PRACTICABLE TO WCA'S	UP TO MAXIMUM CAPACITY AT S-77	UP TO MAXIMUM CAPACITY AT S-80
B (1)	MAXIMUM PRACT CABLE TO WCA'S	6500 CFS AT S-77	3500 CFS AT S-80 (3)
C (1)	MAXIMUM PRACTICABLE TO WCA'S	UP TO 4500 CFS AT S-77	UP TO 2500 CFS AT S-80 (3)
D	MAXIMUM PRACTICABLE TO WCA'S	MAXIMUM NON-HARMFUL DISCHARGES TO ESTUARY WHEN STAGE RISING	MAXIMUM NON-HARMFUL DISCHARGES TO ESTUARY WHEN STAGE RISING (3)
E	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE

NOTES: (1) RELEASES THROUGH VARIOUS OUTLETS MAY BE MODIFIED TO MINIMIZE DAMAGES OR OBTAIN ADDITIONAL BENEFITS.

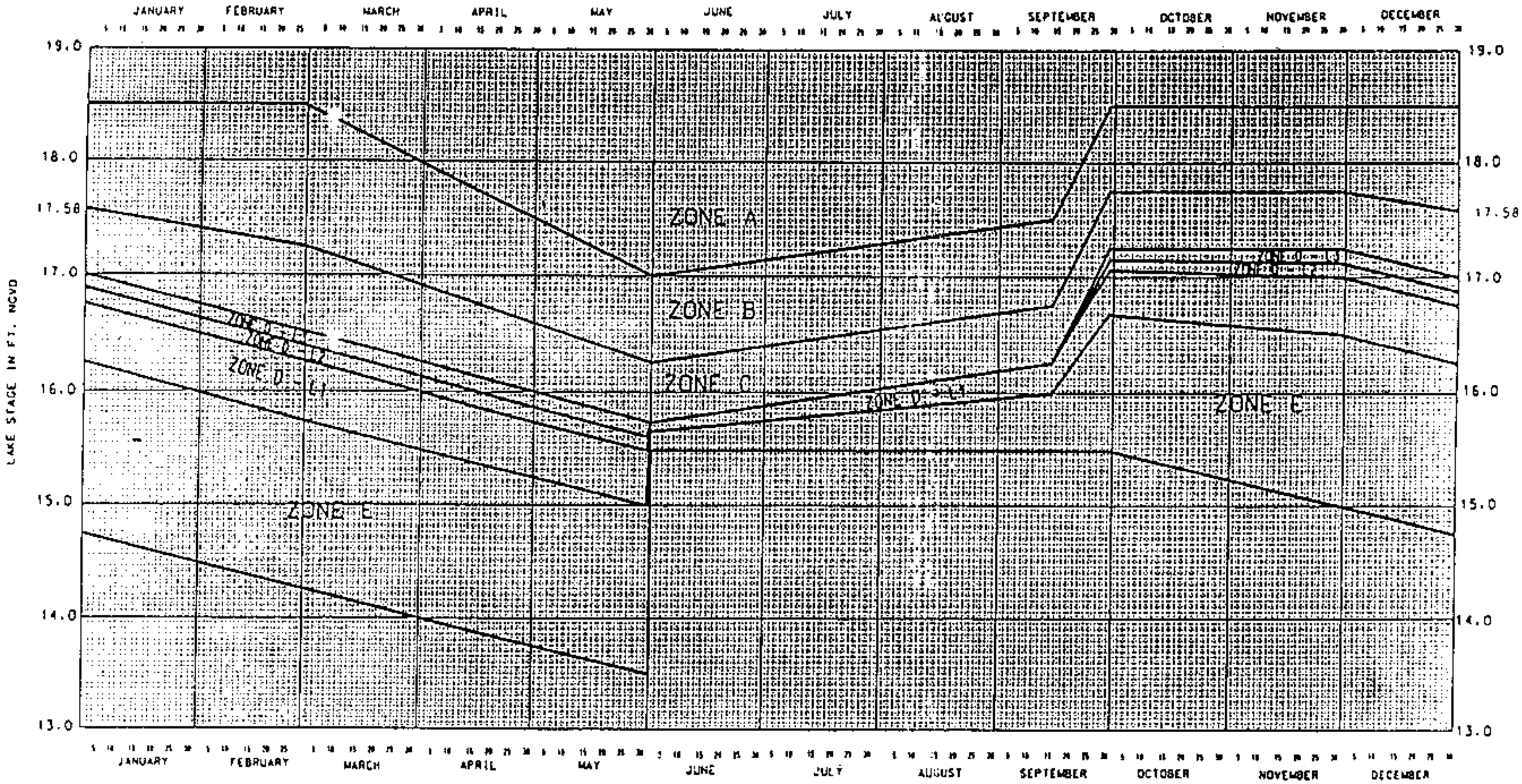
(2) SUBJECT TO FIRST REMOVAL OF LOCAL RUNOFF.

(3) EXCEPT WHEN EXCEEDED BY LOCAL INFLOW.

CENTRAL AND SOUTHERN FLORIDA
INTERIM REGULATION SCHEDULE
LAKE OKEECHOBEE
DEPARTMENT OF THE ARMY, JACKSONVILLE DISTRICT
CORPS OF ENGINEERS, JACKSONVILLE, FLORIDA
DATED: 27 DEC 1994

RUN 25

Figure 2. Alternative Operational Schedule (R22AZE)



LAKE OKEECHOBEE RELEASES

ZONE	AGRICULTURAL CANALS (2)	CALOOSAHATCHEE RIVER (2)	ST. LUCIE CANAL
A	Maximum Practicable Releases to Water Convervation Areas	Up to Maximum Capacity at S-77	Up to Maximum Capacity at S-80
B		6500 CFS	3500 CFS (3)
C		4500 CFS	2500 CFS (3)
D Level 3 Level 2 Level 1		10-day Pulse with a Mean Discharge of: Level 3 = 3000 CFS Level 2 = 2300 CFS Level 1 = 1600 CFS	10-day Pulse with a Mean Discharge of: Level 3 = 1170 CFS Level 2 = 900 CFS Level 1 = 730 CFS
E		No Releases	No Releases

NOTES: (1) RELEASES THROUGH VARIOUS OUTLETS MAY BE MODIFIED TO MINIMIZE DAMAGES OR OBTAIN ADDITIONAL BENEFITS.
(2) SUBJECT TO FIRST REMOVAL OF LOCAL RUNOFF.
(3) EXCEPT WHEN EXCEEDED BY LOCAL INFLOW.

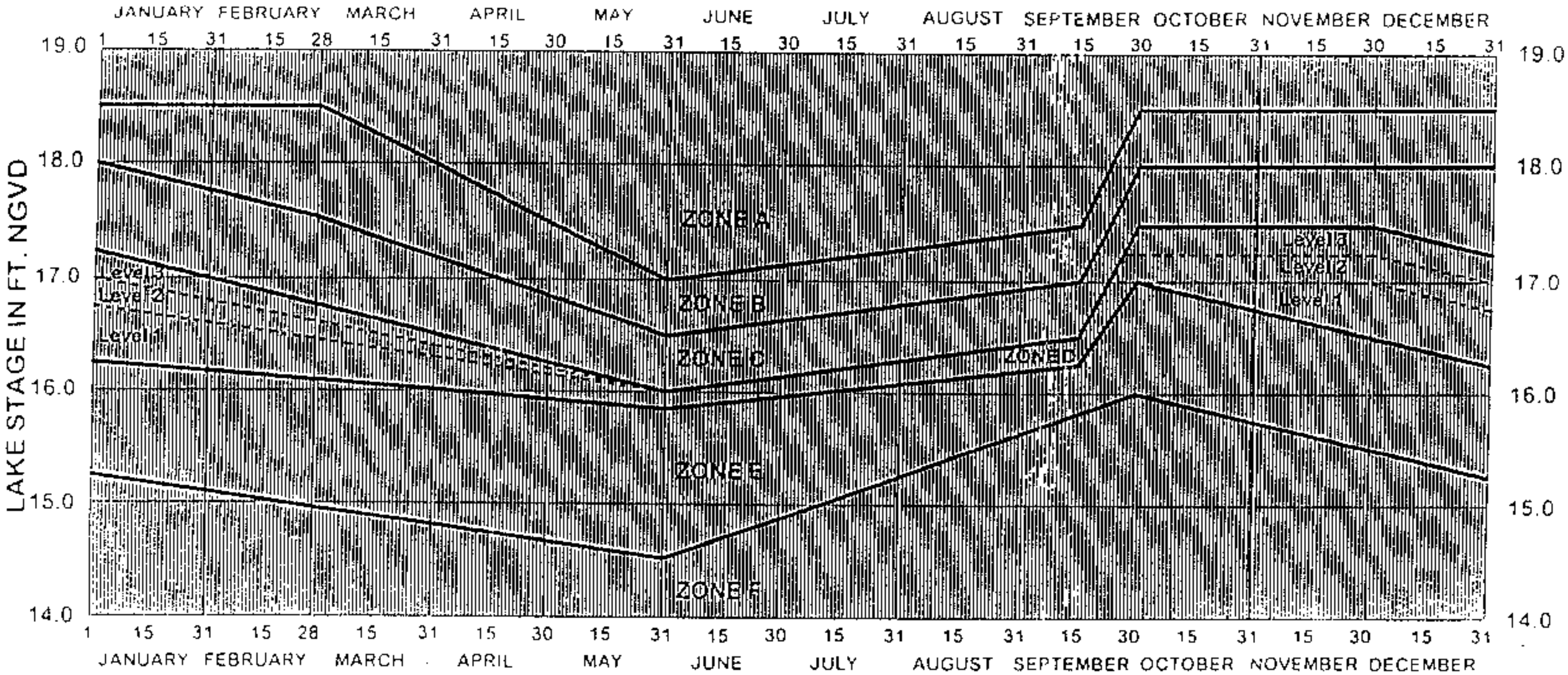
CENTRAL AND SOUTHERN FLORIDA
PROPOSED REGULATION SCHEDULE

LAKE OKEECHOBEE

DEPARTMENT OF THE ARMY, JACKSONVILLE DISTRICT
CORPS OF ENGINEERS, JACKSONVILLE, FLORIDA

R22AZE

Figure 3. Alternative Operational Schedule (COE)



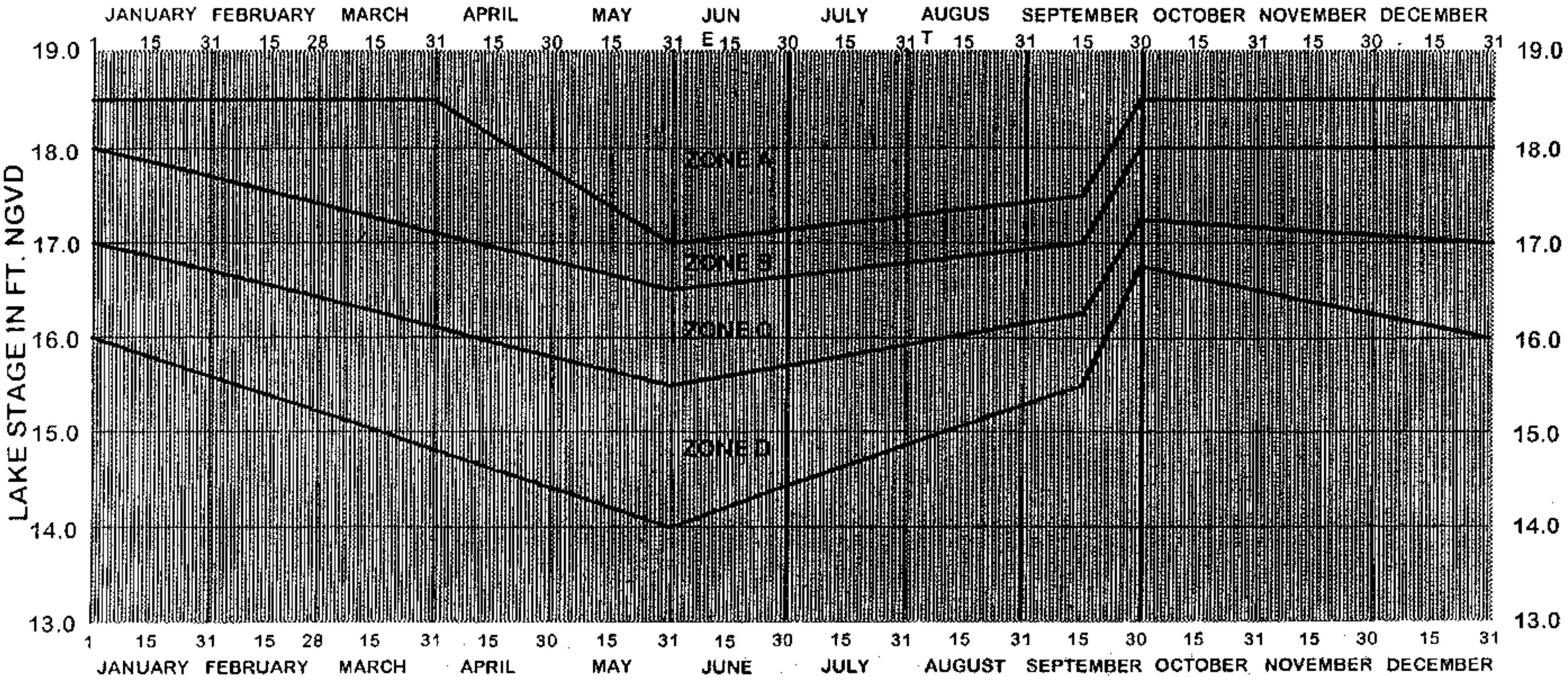
RELEASE THROUGH OUTLETS AS INDICATED

ZONE	AGRICULTURAL CANALS (2)	CALOOSAHATCHEE RIVER (2)	ST. LUCIE CANAL
A	PUMP MAXIMUM PRACTICABLE TO WCAs	UP TO MAXIMUM CAPACITY AT S-77	UP TO MAXIMUM CAPACITY AT S-80
B (1)	MAXIMUM PRACTICABLE TO WCAs	6500 CFS AT S-77	3500 CFS AT S-80 (3)
C (1)	MAXIMUM PRACTICABLE TO WCAs	UP TO 4500 CFS AT S-77	UP TO 2500 CFS AT S-80 (3)
D	MAXIMUM PRACTICABLE TO WCAs	MAXIMUM NON-HARMFUL DISCHARGES TO ESTUARY WHEN STAGE RISING	MAXIMUM NON-HARMFUL DISCHARGES TO ESTUARY WHEN STAGE RISING (3)
E	MAXIMUM PRACTICABLE TO WCAs (4)	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE
F	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE

NOTES:
(1) RELEASES THROUGH VARIOUS OUTLETS MAY BE MODIFIED TO MINIMIZE DAMAGES OR OBTAIN ADDITIONAL BENEFITS
(2) SUBJECT TO FIRST REMOVAL OF LOCAL RUNOFF
(3) EXCEPT WHEN EXCEEDED BY LOCAL INFLOW
(4) SUBJECT TO CANAL CAPACITY; NO RELEASES WHEN IN ZONE A IN WCAs
(5) PULSE RELEASES LEVEL 1, 2, AND 3 AS DESCRIBED IN RUN25

DRAFT PROPOSED REGULATION SCHEDULE
LAKE OKEECHOBEE
DEPARTMENT OF THE ARMY, JACKSONVILLE DISTRICT
CORPS OF ENGINEERS, JACKSONVILLE, FLORIDA
DATED: 4 FEBRUARY 1997

Figure 4. Alternative Operational Schedule (HSM)



RELEASE THROUGH OUTLETS AS INDICATED

ZONE	AGRICULTURAL CANALS TO WCAs (1)	CALOOSAHATCHEE RIVER AT S-77 (1,2,4)	ST. LUCIE CANAL AT S-80 (1,2,4)
A	PUMP MAXIMUM PRACTICABLE	UP TO MAXIMUM CAPACITY	UP TO MAXIMUM CAPACITY
B (3)	MAXIMUM PRACTICABLE RELEASES	NORMAL TO WET: UP TO 6500 CFS DRY: UP TO MAXIMUM PULSE RELEASE	NORMAL TO WET: UP TO 3500 CFS DRY: UP TO MAXIMUM PULSE RELEASE
C (3)	MAXIMUM PRACTICABLE RELEASES	WET: UP TO 4500 CFS NORMAL: UP TO MAXIMUM PULSE RELEASE DRY: NONE	WET: UP TO 2500 CFS NORMAL: UP TO MAXIMUM PULSE RELEASE DRY: NONE
D (3)	AS NEEDED TO ENHANCE NATURAL HYDROPERIODS IN THE EVERGLADES	VERY WET: PULSE RELEASE OTHERWISE: NONE	VERY WET: PULSE RELEASE OTHERWISE: NONE

NOTES: (1) SUBJECT TO FIRST REMOVAL OF RUNOFF FROM DOWNSTREAM BASINS

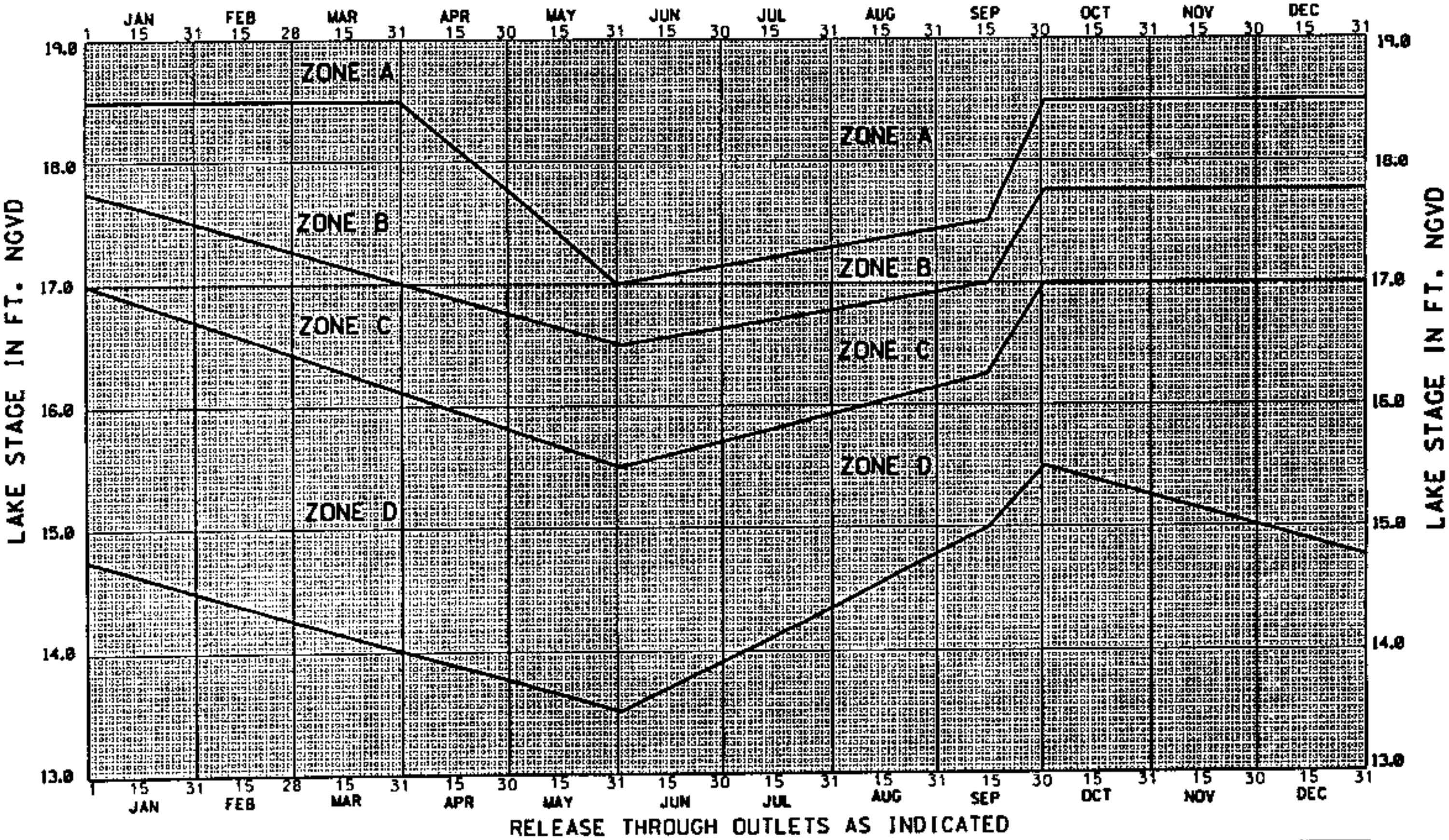
(2) GUIDELINES FOR WET, DRY AND NORMAL CONDITIONS ARE BASED ON: 1) SELECTED CLIMATIC INDICES AND TROPICAL FORECASTS AND 2) PROJECTED INFLOW CONDITIONS

(3) RELEASES THROUGH VARIOUS OUTLETS MAY BE MODIFIED TO MINIMIZE DAMAGES OR OBTAIN ADDITIONAL BENEFITS. CONSULTATION WITH EVERGLADES AND ESTUARINE BIOLOGISTS IS ENCOURAGED TO MINIMIZE ADVERSE EFFECTS TO DOWNSTREAM ECOSYSTEMS. RELEASES SHOULD BE PUMPED WHEN NECESSARY FOR THE ENHANCEMENT OF THE EVERGLADES NATURAL HYDROPERIOD

(4) PULSE RELEASES ARE MADE TO MINIMIZE ADVERSE IMPACTS TO THE ESTUARIES

DRAFT PROPOSED REGULATION SCHEDULE
LAKE OKEECHOBEE
SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WEST PALM BEACH, FLORIDA
DATED: 14 FEBRUARY 1997
HSM

Figure 5. Alternative Operational Schedule (WSE)



ZONE	AGRICULTURAL CANALS To WCAs (1)	CALOOSAHATCHEE RIVER AT S-77 (1,2,4)	ST. LUCIE CANAL AT S-80 (1,2,4)
A	PUMP MAXIMUM PRACTICABLE	UP TO MAXIMUM CAPACITY	UP TO MAXIMUM CAPACITY
B (3)	MAXIMUM PRACTICABLE RELEASES	NORMAL TO WET: UP TO 6500 CFS DRY: UP TO MAXIMUM PULSE RELEASE	NORMAL TO WET: UP TO 3500 CFS DRY: UP TO MAXIMUM PULSE RELEASE
C (3)	MAXIMUM PRACTICABLE RELEASES	WET: UP TO 4500 CFS NORMAL: UP TO MAXIMUM PULSE RELEASE DRY: NONE	WET: UP TO 2500 CFS NORMAL: UP TO MAXIMUM PULSE RELEASE DRY: NONE
D (3)	AS NEEDED TO ENHANCE NATURAL HYDROPERIODS IN THE EVERGLADES	VERY WET: PULSE RELEASE OTHERWISE: NONE	VERY WET: PULSE RELEASE OTHERWISE: NONE

NOTES:
(1) SUBJECT TO FIRST REMOVAL OF RUNOFF FROM DOWNSTREAM BASINS
(2) GUIDELINES FOR WET, DRY AND NORMAL CONDITIONS ARE BASED ON: 1) SELECTED CLIMATIC INDICES AND TROPICAL FORECASTS AND 2) PROJECTED INFLOW CONDITIONS
(3) RELEASES THROUGH VARIOUS OUTLETS MAY BE MODIFIED TO MINIMIZE DAMAGES OR OBTAIN ADDITIONAL BENEFITS. CONSULTATION WITH EVERGLADES AND ESTUARINE BIOLOGISTS IS ENCOURAGED TO MINIMIZE ADVERSE EFFECTS TO DOWNSTREAM ECOSYSTEMS. RELEASES SHOULD BE PUMPED WHEN NECESSARY FOR THE ENHANCEMENT OF THE EVERGLADES NATURAL HYDROPERIOD
(4) PULSE RELEASES ARE MADE TO MINIMZE ADVERSE IMPACTS TO THE ESTUARIES

DRAFT PROPOSED REGULATION SCHEDULE
LAKE OKEECHOBEE
SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WEST PALM BEACH, FLORIDA
DATED: 15 APRIL 1998
WSE

3. OVERVIEW OF THE SFWMM

The South Florida Water Management Model (SFWMM) is a regional-scale, continuous simulation, hydrologic model that was developed and is maintained by the South Florida Water Management District. The SFWMM simulates the hydrology and water management of southern Florida from Lake Okeechobee to Florida Bay. The SFWMM spans a region of over 7,600 square miles with a 2-mile by 2-mile grid; and simulates the system-wide hydrologic response to daily climatic inputs (rainfall and reference evapotranspiration). Other areas tributary to Lake Okeechobee (Kissimmee River, C-43 and C-44, et.al.) are also part of the model, even though they are not explicitly simulated with the 4 square mile grid cells (Figure 5).

The SFWMM simulates infiltration, percolation, evapotranspiration, surface and groundwater flows, levee underseepage, canal-aquifer interaction, well withdrawals for irrigation and/or public water supply, and current or proposed water management structures (canals, spillways, reservoirs, pump, wellfields, etc), and current or proposed operational rules (regulation schedules, drought management plans, etc). The SFWMM is not a succession model; that is, it fixes the land use/cover and associated infrastructure for the entire simulation period. Thus the simulations represent the response of a fixed structural and operational scenario, to historical climatic conditions. This provides a very useful means for comparing the effects of alternative structural and/or operational proposals.

Original documentation of the SFWMM was completed in 1984 (MacVicar, et al, 1984). During the 1990's, the SFWMM was significantly modified as part of the Lower East Coast Regional Water Supply Plan (SFWMD, 1998). Version 3.2 was used for this study and was the first version to include the simulation of the period 1991-95; thus providing 31-year simulations (1965-95). More recent SFWMM development efforts for the Central and Southern Florida Project Comprehensive Review Study (Restudy) have occurred since the April 30, 1997, simulations were produced for the LORSS; however the most recent version of the SFWMM was not used for the evaluation of schedule WSE. Version 3.2 was used to simulate the performance of schedule WSE in order to be consistent with the modeling and base condition assumptions that were used for the other schedules evaluated in the LORSS; thus allowing for an appropriate relative comparison between the schedules.

A recently developed comprehensive documentation report of the SFWMM (SFWMD, 1997 draft) has been reviewed by a peer-review panel. Both the documentation report and the final report from the peer-review panel can be accessed from the world-wide web (www.sfwmd.gov/org/pld/hsm/sfwmm).

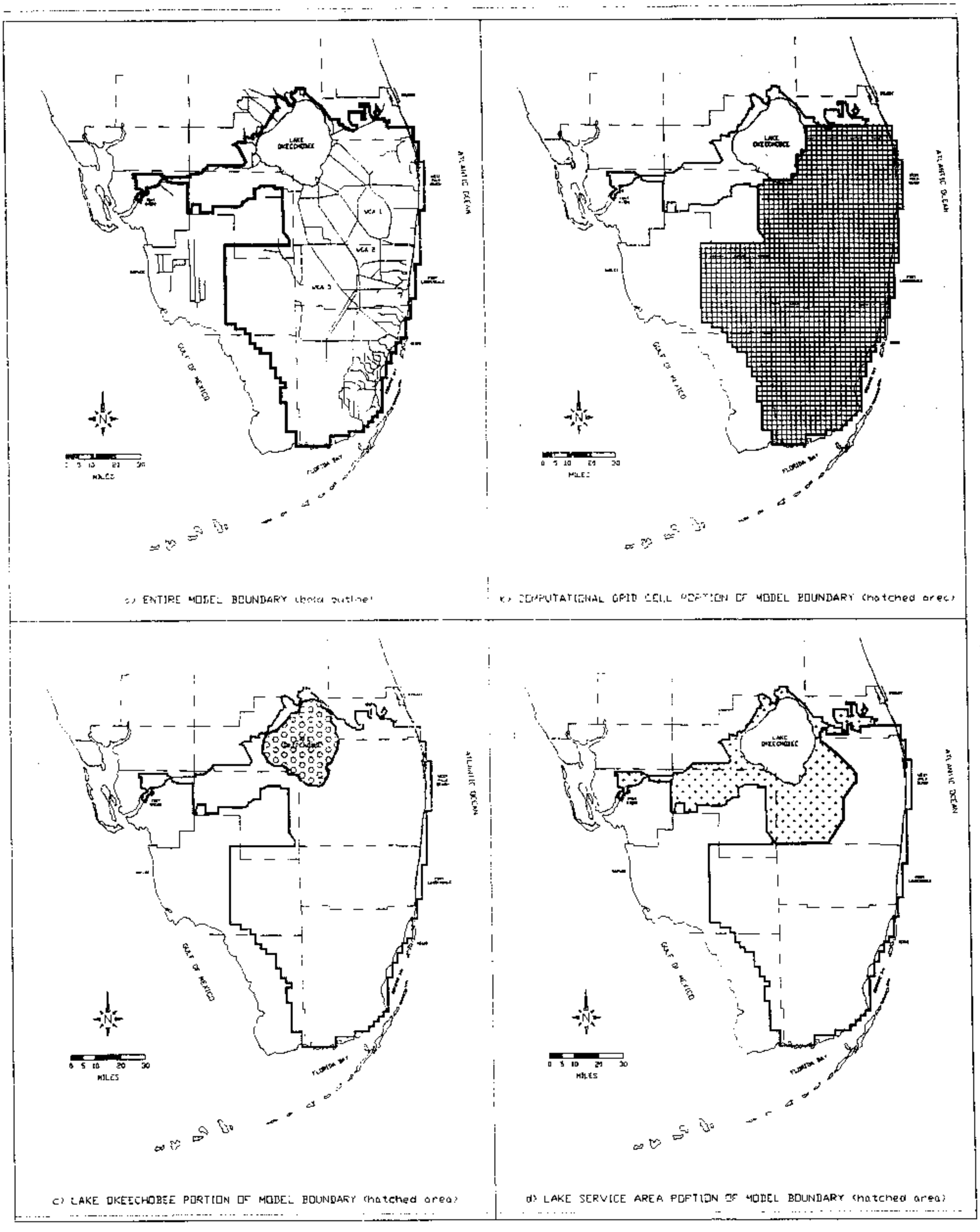


Figure 6. South Florida Water Management Model Boundaries

4. SIMULATION ASSUMPTIONS

Baseline Simulations

Two baseline simulations were developed as part of the Interim Plan for Lower East Coast Regional Water Supply (SFWMD, 1998). These baseline simulations are referred to as the 1990 Base and the 2010 Base, and they represent, respectively, "current (circa 1990)" infrastructure & operations, and future (without project) infrastructure & operations. The 2010 Base can be interpreted as the condition that would result if the LORSS recommended no-action, or no-change from current operations. Therefore, Run25 is assumed as part of the 2010 Base condition.

For the LORSS, several study team members met in the fall of 1996 during the Environmental Performance Measures Workshop and decided that each regulation schedule should be evaluated using both the 1990 and 2010 baseline simulations. The rationale for the decision was based primarily on the uncertainty associated with the status of completion of the projects included in the 2010 base in 1999 - when the recommended regulation schedule is to be implemented. By simulating each schedule using both the 1990 and 2010 baselines, the performance of the schedules under 1999 conditions (land-use, infrastructure and operations) would likely be bracketed. This decision actually simplified the analysis since the SFWMM was already set-up for the 1990 and 2010 baselines.

a. 1990 Baseline Assumptions

1. 1988 land use and associated irrigation demands for the lower east coast service area (LECSA). The LECSA includes the developed portions of Palm Beach, Broward, and Dade Counties.
2. 1989 public water demands at the existing wellfields.
3. 1990 water management facilities and associated operating procedures.
4. Current regulation schedules for WCA-1, WCA-2A and WCA-3A.
5. R25 (Run25) regulation schedule for Lake Okeechobee.

b. 2010 Baseline Assumptions

Same assumptions as the 1990 baseline with the following differences:

1. Projected 2010 land use and associated irrigation demands for the LECSA.
2. Projected 2010 public water demands based on projections made by local government comprehensive plans. These were developed for the LECRWSP.
3. Kissimmee River Restoration Project.
4. Everglades Construction Project: 40,000 acres of Stormwater Treatment Areas (STAs, aka, filtration marshes) and Best Management Practices (BMPs) in the Everglades Agricultural Area (EAA).
5. EAA BMPs are assumed to not reduce EAA irrigation demands on Lake Okeechobee.

6. BMP Replacement Water Rule
7. Modified Water Deliveries to Everglades National Park Project (per the 1992 GDM).
8. C-111 Project (per the 1994 GRR).
9. New WCA-1 regulation schedule (already implemented in 1995).
10. Current regulation schedules for WCA-2A and WCA-3A.
11. Run25 regulation schedule for Lake Okeechobee.

Although, not specifically mentioned in the description of the alternative Lake Okeechobee operational schedules, the simulation of all five schedules assumed pumping to the Water Conservation Areas unconditionally when the Lake Levels are in Zone A. This assumption was made for both the 1990 and 2010 conditions.

<u>2010 Demand Estimates used for the LORSS Simulations</u>

As part of the LORSS and the Central and Southern Florida Project Comprehensive Review Study (C&SF Restudy), an effort was performed by a USACE consultant to project LECSA demands through the year 2050. USACE staff subsequently used the consultant's 2010 demand projections with the spatial and temporal distributions of the LECRWSP 2010 demand data sets, to develop two additional 2010 demand data sets to be used for the simulations. These two new demand data sets represented unrestricted and restricted (with conservation) public water demands.

Simulations were performed to assess the sensitivity of the SFWMM simulations to these new demand data sets. Four simulations were performed and compared for this sensitivity analysis: (1) 1990 Base, (2) 2010 Base, (3) 2010 Base with USACE demand projections for the LECSA (unrestricted), and (4) 2010 Base with USACE demand projections for the LECSA (restricted). Results of this sensitivity analysis are presented in Appendix B.

The conclusion from this analysis was that the simulation results were relatively insensitive to the various 2010 demand projections. Therefore, it was decided to simplify the scope of the analysis by using only the USACE 2010 demand projections for the unrestricted case.

5. SIMULATION RESULTS

An enormous amount of output is generated from each SFWMM simulation. Selected graphical summaries of the performance of each schedule under both the 1990 and 2010 conditions are presented in Appendix C and D, respectively. Appendix E contains the graphical performance summaries for the recently proposed schedule WSE for both the 1990 and 2010 conditions. These graphical summaries are called hydrologic performance indicators, or performance measures. The best hydrologic performance measures are those which provide a quantitative indication of how well (or poorly) an alternative meets a specific objective. These hydrologic performance measures are useful surrogates for ecosystem benefits and impacts; however it is expected that further evaluation of the results from water quality, ecological, and economic perspectives will be performed as part of the LORSS.

Most of the performance measures included in this report were developed as part of the effort to develop the Lower East Coast Regional Water Supply Plan. However, some additional new environmental performance measures were designed for the LORSS during a workshop held in September 1996 in West Palm Beach (Appendix F). Software for these most of these new performance measures was developed by SFWMD staff for the LORSS; and the graphics are included in the appendices.

Results of the alternative operational schedule simulations, as displayed with the performance measure graphics, are organized by geographic area in Appendix C, D, and E, as outlined below.

<u>1990 Condition - Appendix C</u>
a. Lake Okeechobee
b. Lake Okeechobee Service Area
c. Caloosahatchee & St. Lucie Estuaries
d. Everglades WCAs
e. Everglades National Park
f. Lower East Coast Service Areas

<u>2010 Condition - Appendix D</u>
a. Lake Okeechobee
b. Lake Okeechobee Service Area
c. Caloosahatchee & St Lucie Estuaries
d. Everglades WCAs
e. Everglades National Park
f. Lower East Coast Service Areas

<u>WSE Simulations for 1990 & 2010 Conditions - Appendix E</u>
a. Lake Okeechobee
b. Lake Okeechobee Service Area
c. Caloosahatchee and St. Lucie Estuaries
d. Everglades WCAs
e. Everglades National Park
f. Lower East Coast Service Areas

6. TRADE-OFF ANALYSIS

To properly choose the best alternative schedule, it is essential to identify and focus on the most meaningful performance measures. The previous comprehensive evaluation of over 30 alternative schedules (Trimble & Marban, 1988) identified four key measures of performance and provided a trade-off methodology which led to the selection of the regulation schedule that is currently used to manage Lake Okeechobee (Run25).

A similar trade-off analysis is presented in this section as an example to illustrate the concept with a new set of performance measures suggested by the authors. The authors recognize there are other ways of performing the trade-off analysis (Haimes and Hall, 1974); and they recommend the LORSS study team achieve a consensus on the most appropriate methodology and the most meaningful performance measures to use.

Section 6 is divided into 4 subsections: (A) Proposed Performance Measures for the Trade-off Analysis; (B) Results of Trade-off Analysis Comparing Schedules R25, R22, COE and HSM (original comparison); (C) Results of Trade-off Analysis Comparing Schedules R25, R22 and WSE; and (D) Summary of Results of All Five Schedules Simulated for the LORSS.

<u>A. Proposed Performance Measures for the Trade-off Analysis</u>

The following four objectives and associated performance measures were selected by the authors to perform the preliminary trade-off analysis:

Objective 1. Minimize the number of undesirable lake stage events.

Performance Measure: (refer to pages C-9, D-9, and E-9)

Sum the number of undesirable lake stage events defined as follows:

stage > 17ft for > 50 days — *stage < 12ft for > 1 year*

stage > 16ft for > 1 year — *stage < 11ft for > 100 days*

stage > 15ft for > 2 years

Objective 2. Maximize the water supply capability of the lake.

Performance Measure: (refer to pages C-15, D-15, and E-15)

Quantify the percentage of Lake Okeechobee Service Area irrigation demands that were met over the 31-year simulation period.

Objective 3. Minimize harmful high discharges to the estuaries.

Performance Measure: (refer to pages C-12&14, D-12&14, and E-12&14)

Sum the number of times mean monthly discharges to the St. Lucie and Caloosahatchee Estuaries exceeded 2500cfs and 4500cfs, respectively.

Objective 4. Maximize the improvement to hydropatterns in the Everglades.

Performance Measure: (refer to pages C-39, D-39, and E-39)

Quantify the percentage of the WCA system area that matches the mean annual hydroperiod target as estimated by the Natural System Model.

B. Results of Trade-off Analysis Comparing Schedules R25, R22, COE and HSM

Figures 7 and 8 graphically portray the trade-offs among the competing objectives for the 1990 and 2010 conditions, respectively. The scales on these trade-off plots were oriented to show increasing performance with distance away from the origin. Each alternative schedule scores a single value on each of the four axes. Thus, a box is drawn connecting those four points. The bigger the box, the better the alternative performs. An alternative that is superior to all others has a box that extends farther away from the origin on all four axes. Values shown on these figures were obtained from the Appendices (see page 18).

1990 Conditions

From Figure 7 it can be seen that none of the four schedules is totally superior to all the others. For the 1990 condition, schedule 22AZE does the best for the lake ecosystem, and schedule HSM does the best for water supply. Schedules 22AZE and HSM tie for best for the estuaries and the Everglades. Table 4 summarizes the performance relative to the baseline schedule, R25. The trade-off is clearly between schedules 22AZE and HSM. Specifically, the trade-off is between water supply and the lake ecosystem objectives. Schedule 22AZE will improve the ecosystem of the lake, but will decrease the water supply potential of the lake; Schedule HSM will increase the water supply capability of the lake, but will worsen the lake's ecosystem. Further analysis of the significance of the changes from economic and ecological perspectives is necessary to further assess the trade-offs to determine which schedule is best.

Table 4. Change in performance measures relative to Run25 for 1990 conditions

OBJECTIVE	Schedule 22AZE	Schedule HSM	Schedule COE
1. LOK ECOSYSTEM	2 less times(+)	3 more times(-)	no change
2. WATER SUPPLY	2.5% decrease(-)	3.4% increase(+)	0.5%decrease(-)
3. ESTUARIES	10 less times(+)	10 less times(+)	7 less times(+)
4. EVERGLADES	2.2% increase(+)	2.2% increase(+)	1.2%increase(+)

(+) denotes an improvement relative to schedule R25, (-) denotes a worsening.

2010 Conditions

Figure 8 illustrates that for the 2010 condition, as was the case with the 1990 condition, none of the four schedules is totally superior to the others. R25 does the best for the lake ecosystem, and HSM does the best for water supply and the estuaries. All four schedules produce about the same performance for the Everglades. Table 5 summarizes the performance relative to the baseline schedule, R25. The trade-off is again evidently between water supply and the lake ecosystem. But this time the superior schedules appear to be R25 and HSM. Since none of the schedules improve the ecosystem of the lake relative to R25, R25 appears to be superior. However, HSM increases the water supply capability of the lake and decreases impacts to the estuaries, but worsens the lake's ecosystem. Again, further analysis of the significance of the changes from economic and ecological perspectives is necessary to further assess the trade-offs to determine which schedule is best.

Table 5. Change in performance measures relative to Run25 for 2010 conditions

OBJECTIVE	Schedule 22AZE	Schedule HSM	Schedule COE
1. LOK ECOSYSTEM	2 more times(-)	4 more times(-)	1 more time(-)
2. WATER SUPPLY	4.4% decrease(-)	2.2% increase(+)	1.5%decrease(-)
3. ESTUARIES	7 less times(+)	9 less times(+)	5 less times(+)
4. EVERGLADES	no change	no change	no change

(+) denotes an improvement relative to R25, (-) denotes a worsening.

<u>C. Results of Recent Trade-off Analysis Comparing Schedules R25, R22 and WSE</u>

Figures 9 and 10 graphically portray the trade-offs among the competing objectives for the recently proposed schedule, WSE, as compared with schedules R25 and R22. Figure 9 illustrates the trade-offs for 1990 conditions, and Figure 10 illustrates the trade-offs for 2010 conditions. The values shown on the trade-off plots were obtained from the Appendices (see page 18).

1990 Conditions

As compared under 1990 conditions (Figure 9), the WSE schedule performs better than R25 and R22. Performance for the Estuaries and the Everglades are superior to R25 and R22; whereas the performance for water supply is as good as that for R25, and the performance for the Lake Ecosystem is as good as that for R22. Under drought years (figure E-15B), the water supply performance of WSE is slightly better than that for R25.

2010 Conditions

For 2010 conditions (Figure 10), there is not a clearly superior schedule. The increase in demands expected for 2010 conditions produce lower Lake stages and fewer occurrences of high stage events. Thus there are fewer flood release events as compared with 1990 conditions. With fewer high stage events, the comparison of the schedules is more difficult and less conclusive.

Although 2010 conditions assume increased demands on the Lake, the simulations also assume the same historical (1965-95) climate regime will re-occur. If the future climate-regime is wetter than it has been during the past 30 years, then the relative performance of the schedules may be more like that shown for the 1990 conditions. Certain global-scale climate indicators suggest that south Florida may be currently entering into a much wetter climate regime which may last for several decades.

D. Summary of Results of All Five Schedules Simulated for the LORSS

Table 6 summarizes the performance of all 5 schedules. From the 1990 Condition portion of Table 6, it can be seen that schedule WSE is the superior schedule. As compared with the performance of all 5 schedules, the WSE schedule has the best results, or ties for best, for each of the four objectives.

From the 2010 Condition portion of Table 6, there is not a schedule that appears to be superior to the rest. R25 has the best performance for the Lake ecosystem, while HSM has the best performance for water supply and the estuaries. No schedule is superior in performance for the Everglades. It is important to recognize the differences between the 2010 performance of the schedules is relatively small. As noted previously, the significance of these differences from ecological and economic perspectives is necessary to select the best schedule. It is also important to note that the differences in performance between the schedules is relatively small when comparing to the differences from the 1990 to the 2010 conditions. Thus, to further increase the multiple benefits for managing the Lake, other water management components such as storage areas are necessary. The regulation schedule is an important tool for managing the resource, but it has limitations.

Table 6. Summary of Selected Performance Indicators for All Five Schedules
(shaded cells highlight the best performance for the selected hydrologic indicators)

OBJECTIVE	R25	R22	HSM	COE	WSE
1990 Condition					
1. LAKE ECOSYSTEM	9 events	7 events	12events	9 events	7 events
2. WATER SUPPLY	91.9%	89.4%	95.3%	91.4%	91.9%
3. ESTUARIES	66 times	56 times	56 times	59 times	55 times
4. EVERGLADES	63.8%	66.0%	66.0%	65.0%	67.8%
2010 Condition					
1. LAKE ECOSYSTEM	6 events	8 events	10events	7 events	7 events
2. WATER SUPPLY	81.6%	77.2%	83.8%	80.1%	80.9%
3. ESTUARIES	54 times	47 times	45 times	49 times	47 times
4. EVERGLADES	68.4%	68.4%	68.4%	68.4%	67.8%

1. Number of undesirable lake stage events (less is better).
2. Mean annual percentage of supplemental irrigation demands met (more is better).
3. Number of times high discharge criteria were exceeded for the Caloosahatchee and St. Lucie Estuaries (less is better).
4. Mean annual percentage of the area of the WCAs that match hydropattern targets within 30 days (more is better).

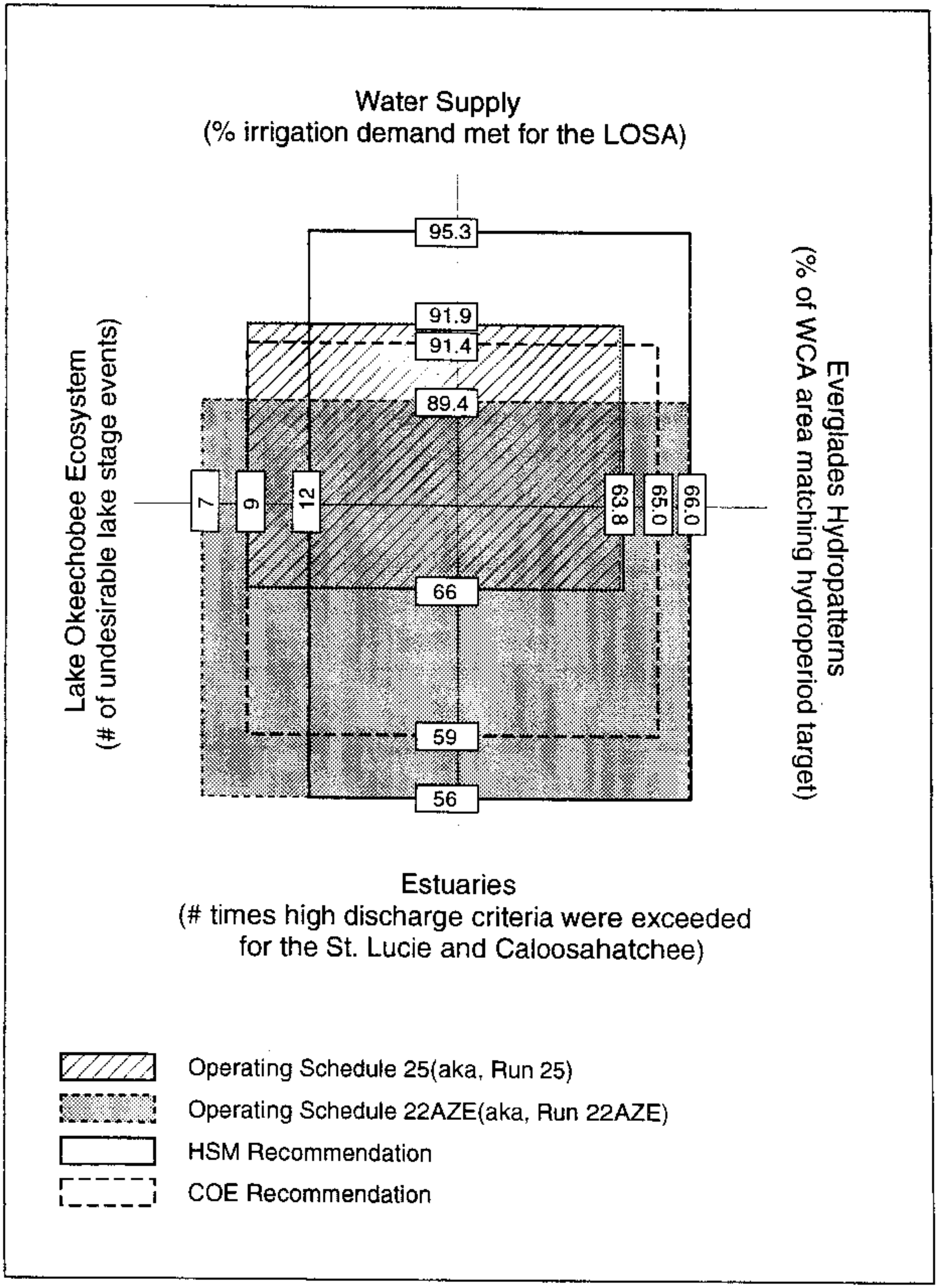


Figure 7. Multi-Objective Trade-off Plot for 1990 Condition

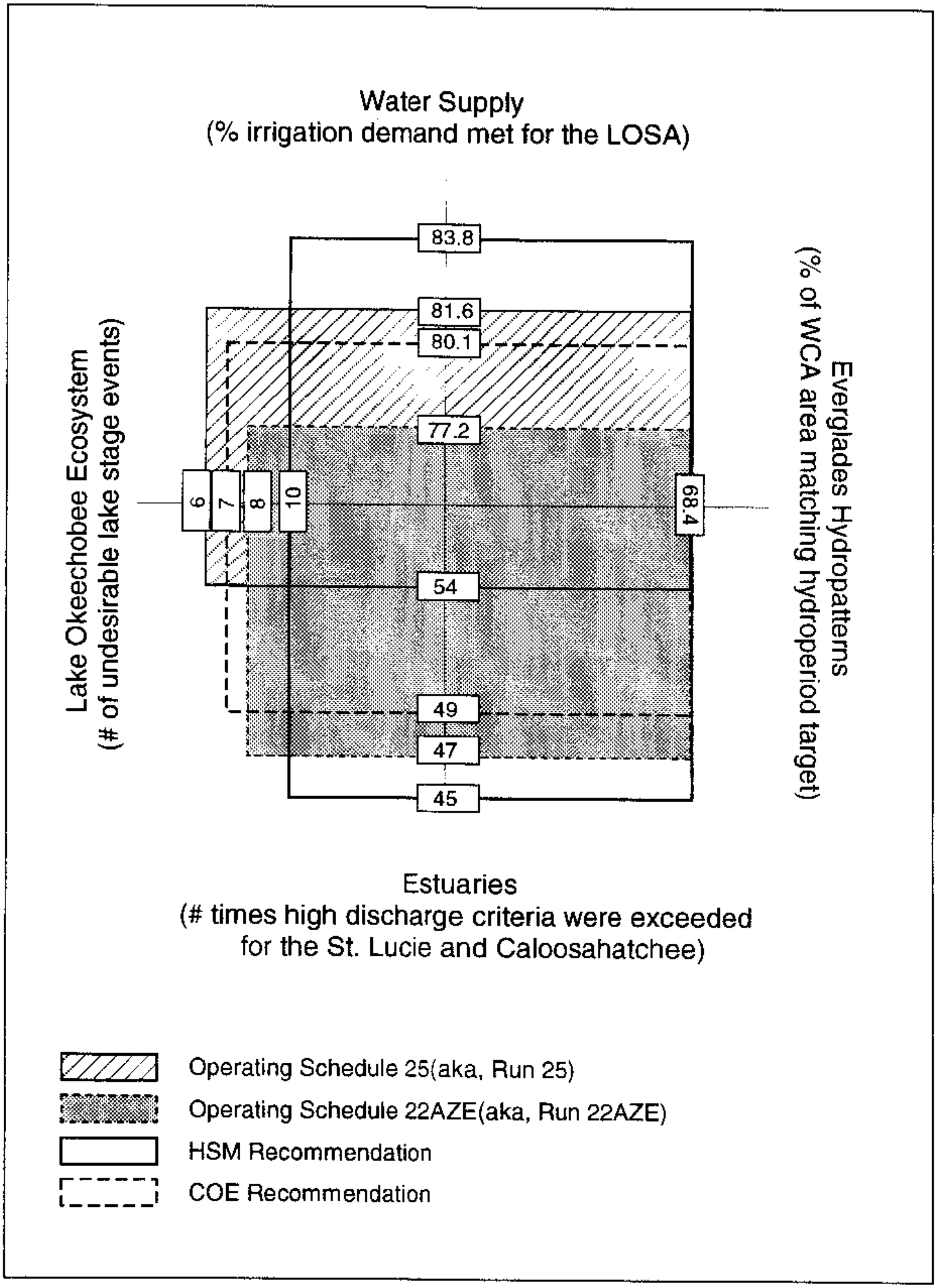


Figure 8. Multi-Objective Trade-off Plot for 2010 Condition

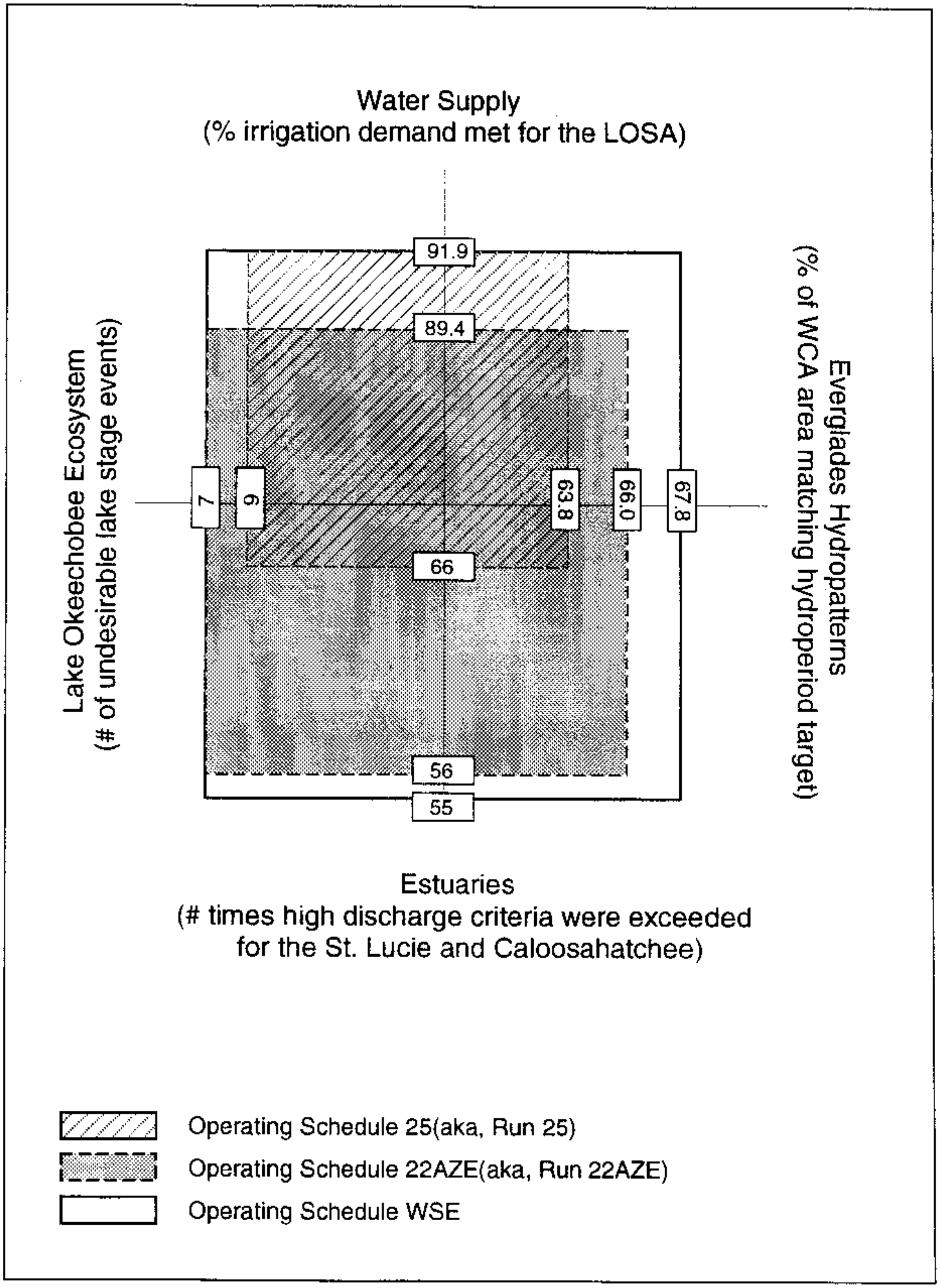


Figure 9. Multi-Objective Trade-off Plot for Operational Schedules 25, 22AZE, and WSE (1990 Condition)

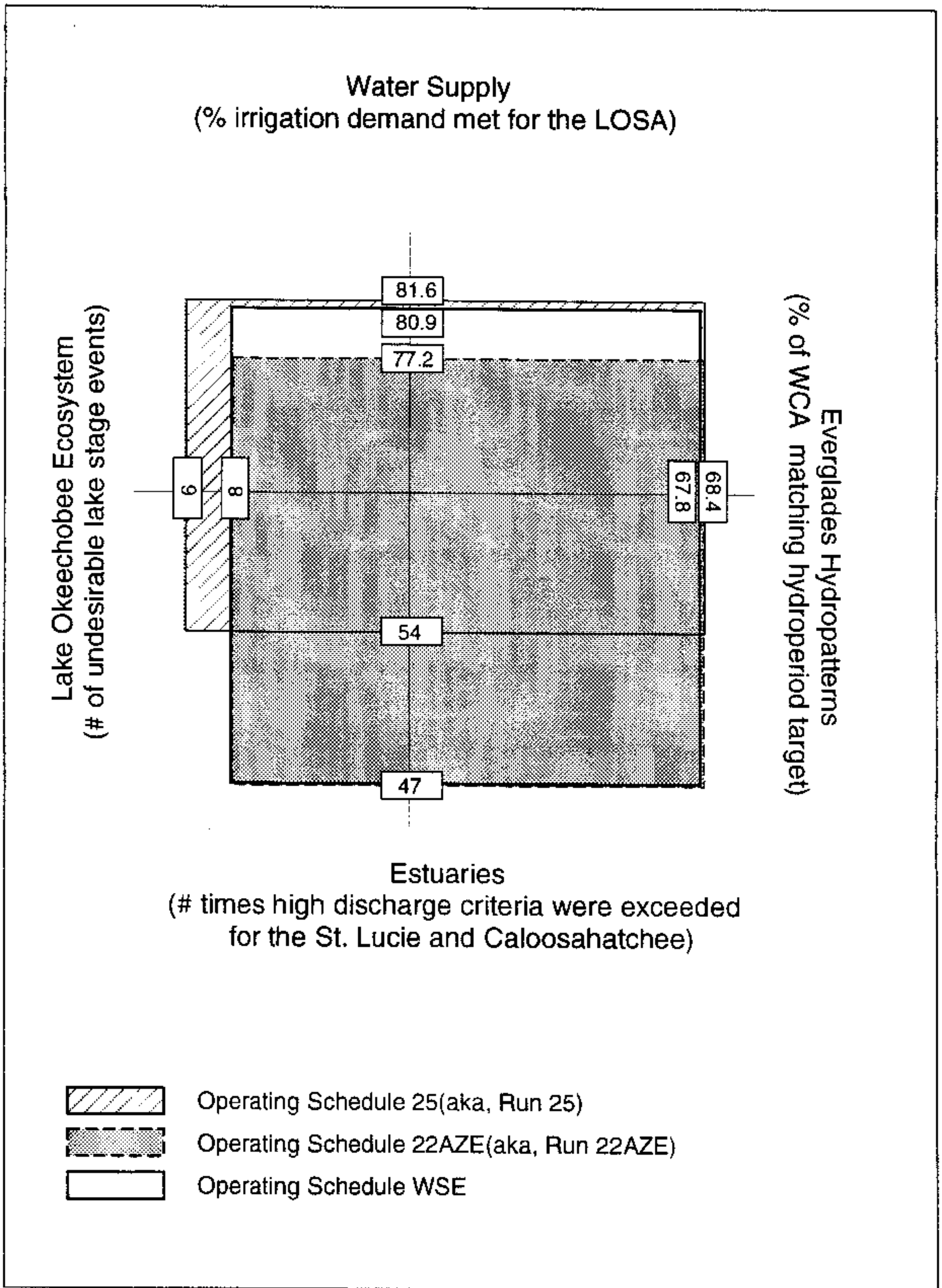


Figure 10. Multi-Objective Trade-off Plot for Operational Schedules 25, 22AZE, and WSE (2010 Condition)

7. SUMMARY

As part of the Lake Okeechobee Regulation Schedule Study, the Hydrologic Systems Modeling Division of the SFWMD performed the simulations and a preliminary analysis of the hydrologic performance of five alternative operational schedules for Lake Okeechobee. Results of the simulations and the analysis were presented in this report. The five schedules evaluated were: (1) the current schedule, R25 (aka Run25); (2) a lower schedule designed to benefit the littoral zone of the lake, R22 (aka Run22AZE); (3) the schedule proposed by the authors as part of the Interim Plan for Lower East Coast Regional Water Supply (HSM); (4) a schedule proposed by the USACE for the LORSS; and (5) a recently developed schedule proposed by the authors (WSE) to better balance the performance of the competing objectives for managing the Lake.

Results of the simulations were summarized in the form of hydrologic performance measures. The most useful of these performance measures quantify the degree to which objectives for managing the lake are met. Numerous hydrologic performance measures were presented in the appendicies of this report.

The authors proposed an evaluation methodology which uses four hydrologic performance measures that were selected to represent four key objectives for managing the lake. These performance measures relate to: (1) the lake ecosystem, (2) water supply capability, (3) estuary health, and (4) Everglades hydroperiod enhancement. From the preliminary trade-off methodology, the key trade-off appears to be between the lake ecosystem and water supply. This trade-off was also identified in previous reports on the subject of Lake Okeechobee regulation schedules.

From the results of the preliminary trade-off analysis, it appears that the recently proposed schedule, WSE, is superior to the rest for 1990 conditions. For 2010 conditions, however, none of the schedules is entirely superior to all the others, although the HSM and WSE schedule have strong advantages since they include more flexible rules and Lake inflow forecasts.

Further analysis of the significance of the changes from economic and ecological perspectives is necessary to further assess the trade-offs to determine which schedule is truly best. Those analysis are part of other efforts that are part of the Lake Okeechobee Regulation Schedule Study, but are beyond the scope of this report.

8. CONCLUSIONS/RECOMMENDATIONS

1. Achieve Consensus on Key Performance Measures and Evaluation Methodology

Most of the performance measures that are presented in this report were developed as part of the Lower East Coast Regional Water Supply Plan. Several new performance measures were designed during a LORSS Environmental Performance Measure Workshop held in September 1996. Additional performance measures were derived in 1997 as part of the River of Grass Environmental Evaluation Methodology (ROGEM) development effort.

There are an infinite number of possible performance measures that can be derived. To provide a comprehensive analysis, it is important to examine the performance of alternative schedules from various perspectives. However, to provide a clear analysis and presentation of the trade-offs in the competing objectives, it is essential that a small set of key performance measures be identified for use in the trade-off analysis that is used for the decision-making.

It is very important that the LORSS team and decision-makers determine the key performance measures to be used for the evaluation of the alternative schedules. Consensus on the method for evaluating the trade-offs in competing objectives for managing the lake should also be achieved.

2. Need for Analysis from Water Quality, Ecological and Economic Perspectives

From the preliminary trade-off analysis provided in this report, it appears as if the key trade-off is between water supply and the lake ecosystem. To assess the significance of the changes from economic, water quality, and ecological perspectives, further analysis is necessary to clearly assess the trade-offs for determining which schedule is best. Furthermore, potential impacts due to increases in phosphorous loads to the Everglades should be estimated.

3. Need to direct more discharges to the EPA

A key finding of this evaluation indicates that introducing a lower operational zone which delivers water only southward to the Everglades allows for much of our valuable water resources to be retained within the regional hydrologic system. This has tremendous potential for improving the hydroperiod of the Everglades and reducing the impacts of large freshwater discharges to the estuaries. However, if these releases to the Everglades are made unconditionally, as is proposed with schedules R22 (Run22AZE) and COE, then the potential for water shortages will increase significantly.

The rules proposed in the HSM and WSE schedules make these southward releases in the new proposed zone only when it would be desirable for enhancing Everglades hydroperiods. When this policy is put into practice together with the more flexible operational rules that take advantages of the state of the art in climate research, it is possible to eliminate this drawback of increased water shortages while still realizing the benefits to the Everglades. However, it is recognized that the Lake Okeechobee littoral zone does not receive the desirable benefits that were targeted with the design of R22.

4. Need to include Global Climate Indices and regional hydrologic forecasts in regional water management.

Recent breakthroughs in the diagnostics of climate variability on monthly to decadal time scales provide a valuable mechanism for the advancement of the level of proficiency of regional water management. This potential for progress results from increased lead times of forth-coming climate anomalies that may persist for extended periods. These anomalies may occur in the form of long-term departures from average climate conditions and/or a distinct change in the likelihood of occurrence of extreme events. When these anomalies are recognized as being associated with larger-scale prolonged climate phenomena, the advantages of the most adaptable operational schedule are significant. This opportunity for increasing the efficiency of our the regional hydrologic system is very timely considering the challenges that we face in managing our future water resources in central and southern Florida.

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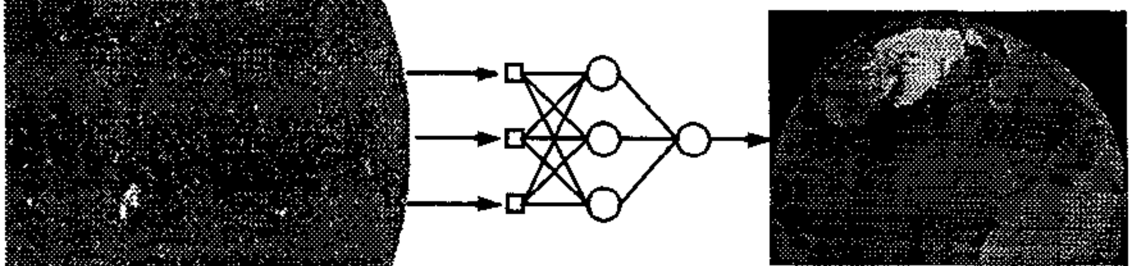
APPENDIX A. Methodology for Lake Inflow Predictions

The manuscript entitled "Including the Effects of Solar Activity for More Efficient Water Management - An Application of Neural Networks" is provided on the following pages. The research was presented at the Second International Workshop on Artificial Intelligence Applications in Solar-Terrestrial Physics held on July 29-31, 1997, in Lund Sweden. The manuscript is included in the Workshop proceedings which are being published in a European Space Agency special report (ESA SP-X).

Second International Workshop on Artificial Intelligence Applications in Solar-Terrestrial Physics

Lund, Sweden, 29-31 July 1997



Courtesy of the Polar/VIS. The VIS is an instrument of the NASA Goddard Space Flight Center.

...kshop on AI Applications in Solar-Terrestrial Physics took place in Lund 1993, a new era of ... observations has started. Many discoveries have been made with satellites such as Yohkoh, ...HO, WIND, GEOTAIL and Polar. These satellites are producing an enormous amount of data that ... new techniques for data analysis. Artificial Intelligence (AI) methods, including neural networks, expert systems, genetic algorithms, fuzzy logic, fractal analysis and hybrid systems, offer such techniques for automated analysis, data reduction, classification, pattern recognition, function approximation and predictions. Demands for speed and automation have also stimulated development of hardware implementations such as neural chips. For future observations, even clusters of intelligent satellites, are discussed.

INCLUDING THE EFFECTS OF SOLAR ACTIVITY FOR MORE EFFICIENT WATER MANAGEMENT: AN APPLICATION OF NEURAL NETWORKS

P.J. Trimble, E.R. Santee, C.J. Neidrauer

South Florida Water Management District, West Palm Beach, Florida, USA

ABSTRACT

Lake Okeechobee is the second largest freshwater lake by area lying wholly within the boundaries of the United States. The competing objectives associated with the water management of this large body of water are becoming increasingly challenging to satisfy. This is in part due to rapid development of the region as well as an ever growing awareness of the needs and sensitivities of the natural ecosystems within the region. The findings of this report demonstrate the advantages of having more flexible water management rules that recognize natural climate variability as it occurs on seasonal to decadal time scales. The variability of climate identified with solar activity, El Nino events, and changes in the strength of the Atlantic Ocean thermohaline current, are integrated with the aid of a neural network to make six month inflow forecasts for Lake Okeechobee. By incorporating the hydrologic forecast into the Lake operational rules, it is demonstrated that the objectives of water management can be more proficiently satisfied. Temporal distribution and strength of solar activity as indicated by geomagnetic disturbances and sunspot activity are demonstrated to be important inputs for the seasonal hydrologic forecast for Lake Okeechobee.

Key words: inflow forecast, climate variability, efficient water management, geomagnetic activity, sunspots, neural network.

1. INTRODUCTION

Lake Okeechobee is the "liquid heart" of southern Florida. The surface area of the Lake is approximately 1970 km^2 and has a storage capacity over 4×10^9 m^3 in which excess water may be stored during the wet periods for subsequent use by agricultural and municipalities during drier periods. It is also an important source of water for the vast wetlands to its south known as the Everglades. Due to the potential for heavy rains and severe tropical storms in south Florida, water levels must be carefully monitored to ensure that they do not rise to levels that threaten the structural integrity of the levee system surrounding the Lake. The natural ecosystems within the Lake and those located within the downstream estuaries and wetlands are also very sensitive to the temporal and spatial distribution of releases from the Lake.

Zhang and Trimble (1996 a , b) developed a methodology for predicting Lake Okeechobee inflows from solar and global indices with the application of an artificial neural network. The current paper reports on the refinement of the earlier approach and a demonstration of the improved water management efficiency that may be achieved by including the forecast in Lake Okeechobee operational guidelines.

2. CLIMATE SHIFTS AND WATER MANAGEMENT

Weather forecasting is the science of predicting the likely future sequence of weather events. Weather systems are governed by complex interactions of physical and dynamic processes which are very sensitive to a diverse array of atmospheric variables. Small differences in these variables at one moment of time can eventually lead to large variations in the atmospheric behavior at a later time. The limited availability of high quality fine resolution meteorological data for atmospheric models bounds the lead time that can be produced with weather forecasts. Typically such forecasts are considered reliable for only a few days and seldom longer than a few weeks.

Regional water management systems that include large lakes and reservoirs with extensive tributary and water use basins require longer lead forecasts so that operators can make significant adjustments early enough to minimize adverse impacts to sensitive ecological systems, while maintaining adequate levels of flood protection and water supply. This is the situation that exists for Lake Okeechobee. Amplification of the Lake hydrologic response significantly narrows the window of opportunity for operational decisions. With the significant advances in climate research in recent years, climate forecasting has emerged as a plausible mechanism for improved water management. Climate forecasts predict shifts in atmospheric conditions that may persist for months, years or even decades. A shifted climate may be recognized locally as a persistent change in the expected mean and extremes of rainfall events over prolonged periods.

A rainy weather event in the domain of a climate shift towards drier conditions may be mistaken for a return to more normal or even wetter than normal climate conditions, if it is just perceived from a local perspective. However, it becomes of great significance for water management when the local climate anomaly is recognized as being associated with other larger (continental or global) scale climate events. Ramusson and Arkin (1993) emphasized the necessity for having a global perspective in order to understand persistent shifts of regional climate.

3. VALUABLE INDICATORS FOR FLORIDA

Indeed, a large portion of the variations of south Florida's climate and hydrology has been found to be associated with solar and large-scale global processes. Associations between climates at distant locations of the world are known as teleconnections. These teleconnections tend to be most easily recognized by somewhat cyclic anomalies of atmospheric and oceanic variables. The detailed description of all these anomalies is beyond the scope of this report. However, a few global and solar indices are readily available that provide useful information for forecasting regional hydrologic conditions within Florida.

3.1 Solar Indices

Certain global climate and oceanic fluctuations that occur with a regular frequency appear to have their origins associated with solar activity. Solar sunspot activity displays a cyclic pattern with an approximate periodicity of 11 years. The periods actually vary between 9 and 14 years. Periods tend to be shorter when the magnitude of the sunspot maximum is larger and longer when the magnitude of the sunspot peak is smaller. The 20th century has been a period with very high solar activity with a corresponding shorter than average cyclic period of 9.7 years (Christensen and Lassen, 1991). Between each cycle there is a reversal in the direction of the sun's magnetic field. Therefore conditions begin a new cycle about once every 22-years. This cycle is known as the Hale cycle.

In spite of increasing statistical evidence that indicates a significant portion of the earth's climate variability is associated to variations of solar activity, the exact mechanisms of these associations are not completely understood. The changes in the energy flux that occurs across the outer bounds of the Earth's atmosphere during the variation of sunspot activity appears to be too small to account for the observed climatic fluctuations. Willet (1953, 1987) has elaborated that the solar wind penetration of the geomagnetic field and upper atmosphere allows strong spot heating of the earth's atmosphere, which disrupts the zonal weather circulations. This, he contended, would allow such activity to contribute significantly to climate fluctuations without appreciable changes in energy flux. The aa index of geomagnetic activity was taken by Willet to be the best indicator of solar wind disturbances. This index, as does sunspot activity, follows an approximate 11- year cycle, but generally lags the sunspot cycle and contains many more perturbations. Christensen and Lassen (1991) also suggested that solar parameters other than the sunspot number may be better indicators of solar variations and their influence on the Earth's climate.

Recent research of Labitzke and van Loon (1989, 1992, 1993) provide more recent evidence that an important connection exists between solar cycles and the Earth's climate. Haigh (1996), successfully simulated observed shifts of the subtropical westerly jets and changes in the tropical Hadley circulation that appear to fluctuate with the 11-year solar cycle. Photo-chemical reactions in the stratosphere are included in the model that enhance the effects of the variations of the solar irradiance. Even a small shift in the strength and positioning of these global scale climate systems would have significant effects on Florida's climate. Balliunas and Soon (1996) concluded from long term solar records that solar-brightness variations can explain the majority of the past record of terrestrial global temperature fluctuations. They indicated that the variable length of the solar magnetic cycle correlates nearly perfectly with the 11-year moving average of global temperature since 1750. Reid and Gage (1988), Reid (1991), and White (1996) reported on the similarities between secular variations of solar activity and that of the global sea surface temperature.

In summary, solar activity affects the Earth and its atmosphere in many ways over different time scales. These may be broken down into the following categories:

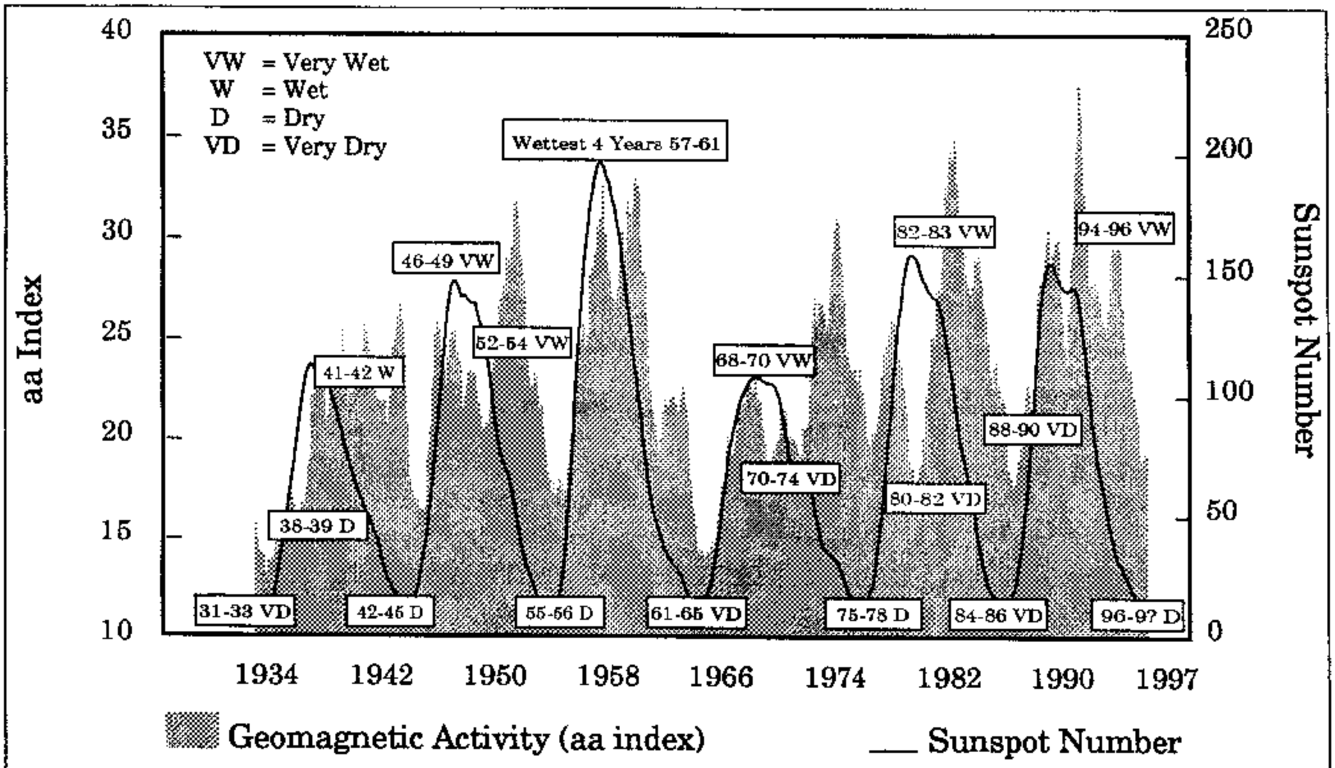
1. Short duration sporadic events,
2. The 11 - and 22 - year sunspot cycle,
3. Longer solar cycles

All three of these categories appear to contribute significantly to climate variations in south Florida.

Figure 1 labels the most significant anomalies in the hydrologic record of Lake Okeechobee compared to that of solar activity as estimated by the sunspot number and geomagnetic activity. These hydrologic anomalies are defined in terms of water years which extend from June of the first year through May of the following year. Each water year was classified based on the magnitude of the inflow volume for illustration purposes. The inflow term includes surface inflows plus the volume of net rainfall that falls directly on the Lake. Years with annual inflows less than 3.5×10^9 (2.5×10^9) m^3 are classified as being dry (very dry), while inflows greater than 6×10^9 (7×10^9) m^3 are classified as being wet (very wet). When a period of several wet or dry years are in sequence, the period is labeled according to the wettest or driest year of each sequence.

Sporadic solar activity may be represented by peaks in the geomagnetic activity. Large Lake inflow periods that occurred within southern Florida during the periods of 1946-1949, 1952-1954, 1957-1961, 1982-1983 and 1994-1996 appear to have been closely associated with solar activity. Extended dry periods are consistently associated with minimums of either geomagnetic activity or minimums of the 11-year sunspot cycle. On a longer time scale, decadal variations of Lake Okeechobee inflows appear to be related to the magnitude of the 11-year solar cycle from 1930 through 1970. However, the relationship becomes less obvious during the more recent years. This climate break is discussed in more detail in the following sections

An important feature illustrated in Figure 1 is that different types of solar activity do not always fluctuate in synchronize fashion relative to each other. The 1979-1980 sunspot maximum was accompanied by an uncharacteristic lull in geomagnetic activity. This 1980-1981 period was marked by the occurrence of the lowest inflow for the period of analysis. During other periods it may be speculated that the geomagnetic activity is the only significant indicator of the Floridan climate anomalies.



Note: Wet and dry period labels are only positioned to indicate the apparent association of these events with the 11-year solar cycle and geomagnetic avtivity. The magnitude of Lake Okeechobee inflow for each year appear in Table 1.

Figure 1. Indicators of Solar Activity and Notable Lake Okeechobee Inflow Periods

However, the authors visual inspection of the data indicates that this may not be the case.

It appears that climate conditions that favor extreme hydrologic events are better recognized by considering both geomagnetic and sunspot activity. It is hypothesized at this time that these two indicators represent different physical mechanisms for solar activity to influence climate. The geomagnetic activity, as suggested by Willet (1987), represents solar wind disturbances which are believed to be associated with the disruption and breakdown of zonal flows and increased storminess in Florida. Changes of solar energy output that occur over longer time periods. These variations of solar energy flux, as suggested by Haigh (1996), are believed to be associated with subtle changes in the strength and positioning of the of the Hadley Circulation. These subtle changes potentially would likely cause shifts in Floridian

3.2 El Nino - Southern Oscillation

The El Nino-Southern Oscillation (ENSO) is a complex interaction of oceanic and atmospheric processes in the tropical Pacific. This system of processes is associated with climate anomalies world-wide. The Floridian climate has its most significant statistical association with the ENSO process during the winter months. During periods of persistent above normal ocean temperature along the equatorial Pacific Ocean (El Nino event) greater than normal winter rainfalls are expected in Florida. Likewise, during persistent periods of below normal ocean temperature in the same region of the Pacific Ocean (La Nina event) less than normal winter rainfalls are normally experienced in Florida (Hanson and Maul, 1991). The Southern Oscillation Index (SOI) computed from the sea level pressure anomalies is used as an indicator of the strength and phase of the ENSO.

The SOI was selected over sea surface temperature anomalies (SSTA) because it has a much longer period of historical record available. The sea surface temperature (SST) record for El Nino events is available beginning in 1950 while the SOI period of record begins prior to 1900. This longer period of record is particularly valuable for analyzing the relationship of the variations of the Floridian climate and hence hydrology to various global atmospheric-oceanic conditions.

3.3 Atlantic Ocean Thermohaline Current (AOTC)

Broecker (1991) outlined the theory of the great ocean conveyor. This is a global system of ocean currents that is driven by density differences caused by variations in salinity and temperature. Broecker hypothesized that variations of these currents may cause abrupt shifts to the global climate. Gray et al (1997) recognized the importance multi-decadal shifts of the Atlantic Ocean portion of the global ocean conveyor may have on tropical activity and climate fluctuations. Strong phases of the current are associated with increased, more intense tropical activity and weaker, less numerous El Nino's. Florida experienced much wetter conditions and more intense tropical storms prior to 1970, the last period the AOTC was recognized as being in the strong phase prior to 1994. The 1970 - 1993 is the period reported by Gray et al for which the AOTC has been reported as being in a weak phase. They suggest that the general strength of this current may be estimated by subtracting South Atlantic Ocean SSTA from North Atlantic Ocean SSTA averaged over broad regions of each ocean basin. When the North Atlantic Ocean is experiencing warmer anomalies and the South Atlantic Ocean cooler anomalies the AOTC is described as being in a stronger phase. When the anomalies reverse themselves, the current is described as being in a weaker phase. Evidence suggests that the AOTC has recently reentered the strong phase of the conveyor current. This would indicate more intense tropical activity and very wet conditions may be on the horizon for Florida. This statement is supported by recent SSTA and more frequent intense Hurricanes within the Atlantic Ocean Basin. The North Atlantic Ocean SSTA minus the SSTA has recently became positive for the first time in 25 years (during the 1994-1995 water year). The magnitude of the difference in anomalies normally range between 0.3 to 0.5 degrees centigrade. The value remained continually positive from 1930 through 1969 and continually negative between 1970 and 1994. Gray et al's 1997 report covers past variation of the strength of the AOTC and the effect this variation had on the climate regime of the Atlantic Ocean basin.

3.4 Predicting Regional Climate Shifts

Successful interpretation of the effects that large-scale global and solar processes have on regional climate anomalies requires that the interactions of these processes be considered. A detailed visual inspection of historical data reveals some potentially useful relationships. These relationships are discussed in the following sub-sections.

3.4.1 Interaction of ENSO Events and Solar Activity

El Nino events that occurred during the peak solar activity have more pronounced rainfall anomalies (greater increases in rainfall) in Florida. The El Nino events of 1957-1958, 1982-1983, and the 1990s are primary examples of this type of episode. The 1965-1966, 1972-1973, 1977-1978 and 1986-1987 events are examples of moderately strong El Nino's events that had minimal effect on Florida's hydrology. These events occurred within periods of lesser solar activity.

Enfield and Cid (1991) presented evidence that when solar activity is strong, El Nino-Southern Oscillation (ENSO) events, are spaced farther apart with periodicity being strongly influenced by the Sun. During weaker solar activity the events occur closer together and are more influenced by the internal dynamics of the ENSO system. Mendoza et al (1991) reported on the increased likelihood of ENSO events during particular phases of the 11-year solar cycle. It appears very plausible that solar activity influences Florida's climate and hydrology indirectly by its influences on the periodicity and onset of El Nino events.

3.4.2 Interaction AOTC and Solar Activity

Hydrologic drought in Florida tend toward periods of minimum solar activity and the periods shortly thereafter. This relationship exists even during strong phase of the AOTC. The 1996-1999 period is a period to be cognizant of the increased potential for drought due to the phase of the solar cycle. The exact timing of these events depends on the phase and strength of the El Nino. Even if a strong El Nino event does occur, it generally has less effect on Florida's rainfall during periods of lesser solar activity. Once this potentially dry period passes, south Florida appears headed to a climate regime similar to that which existed from 1940 through 1960. This forecast is based on the return to a strong AOTC as reported by Gray et al and a general consensus that solar cycle 23 should continue the recent trends of strong to very strong sunspot cycles that have occurred during the middle and latter part of the 20th century (Joselyn et al, 1996). This shift in climate regime will make the 1994-1995 seemingly very large inflow event a much more common occurrence.

When considered jointly, the *AOTC* and long term level of *solar activity* appear to account for a significant portion of the multi-decadal variability of Florida's climate.

4. FORECASTING LAKE OKEECHOBEE INFLOWS

The ability to forecast climate shifts that affect a full range of water management objectives is very desirable. However, the complexity of the solar-terrestrial and oceanic-atmospheric interaction make the ability to forecast regional climate anomalies by more traditional statistical methods difficult. This paper applies an artificial neural network for predicting Lake Inflows.

4.1 Neural Networks

Neural networks have received attention from many professions. In water resources and hydrology, several applications may be cited (Karunanithi, 1994; Smith and Eli 1995; Crespo and Mora, 1993; Grubert, 1995; Raman and Sunilkumar, 1995; Derr and Slutz, 1994). Appealing aspects of neural networks are their applicability to complex non-linear problem sets, their adaptiveness to adjust to new information and their ability to make predictions from inputs in which the relationships between the predictors and the predicted are not completely understood. Among the variety of neural network paradigms, back-propagation is the most commonly used and has been successfully applied to a broad range of areas such as speech recognition, autonomous vehicle control, pattern recognition and image classification. This is the methodology selected for making the inflow forecast.

The most significant adaption to the original methodology developed by Zhang and Trimble (1996) was the inclusion of the strength of the AOTC as a predictor of Lake Okeechobee inflow. In addition, a logarithmic transformation of Lake Okeechobee inflow was made to reduce the skewness of the data set. After an extensive effort was performed which involved the evaluation of different network configurations the configuration with 7 input neurons and 14 hidden layer neurons was selected for making the inflow forecast.

4.2 Data for Training and Testing

Seven parameters were processed for predicting Lake Okeechobee inflows. These include:

1. the Southern Oscillation Index (SOI),
2. the sunspot number,
3. trend in sunspot number,
4. maximum sunspot number of each cycle,

5. geomagnetic index,
6. AOTC index, and
7. the month of the year.

Indices were smoothed with a six month running average. Therefore, each of the indices used for the inflow predictions was the average value of that index during the previous six month period. Two exceptions to the smoothing were made. The first exception was the AOTC index which was simply input as a step function . The strong state of the current was input through 1970 and after 1993. The period between 1970 through 1994 was defined as being in the weak state based upon on-going research (Gray et al, 1997).

The second exception is the maximum sunspot number of the current cycle. During the training and testing periods the actual value was used. During the period the neural network is used for hydrologic predictions, it is planned to use the forecast of the forthcoming 11-year cycle for the rising phase of the sunspot cycle. Forecast are available from various sources including NASA. On the declining phase the actual maximum sunspot number may be used.

Estimated Lake inflow values were obtained from the United States Army Corps of Engineers Rules Curve and Key Operating Manual prior to 1965 (USACE, 1978). After 1964 the values were computed from data collected by the South Florida Water Management District (SFWMD). A complete data set of climate indices and Lake inflows from 1933 through 1996 is available for training and testing each neural network configuration.

Table 1 summarizes the annual average climate indices and annual inflow volumes according to the volume of inflow that occurred each water year. The solar and ENSO indices are reported in terms of .5 unit normal deviates. The AOTC index is depicted as a step function with a strong phase (+) and a weak phase (-). Table 1 is a summary of inputs and does not represent the actual values of input that are used for training and testing the neural network.

Table 1. Annual Lake Inflow Versus Averaged Annual Values of Climate Indices [Each Symbol +/- .5 unit normal deviate]

Water Year [June-May]	Sunspot Number	Geo-Magn. [aa]	ENSO Index [-SOI]	AOTC Index	Lake Inflow [$m^3 10^6$]	Rank
1959-1960	+++	++		+	9558	1
1947-1948	++			+	9382	2
1953-1954	--		++	+	9252	3
1960-1961	+	++++	-	+	8752	4
1969-1970	+	-	+	+	8179	5
1982-1983	+	----	+++	-	7875	6
1957-1958	++++	--		-	7756	7
1994-1995	-	--	---	+	7064	8
1995-1996	--			+	6407	9
1968-1969	+			+	6333	10
1948-1949	++			+	6156	11
1941-1942		-	++	+	6080	12
1992-1993	+	-	++++	-	5831	13
1945-1946	-	--	-	+	5705	14
1933-1934	--	--	-	-	5644	15
1940-1941			+	+	5472	16
1954-1955	--	--		-	5268	17
1951-1952		--		-	5268	18
1934-1935	--	-----		+	5258	19
1949-1950	++			-	5164	20
1936-1937		--		-	5045	21
1978-1979			-	-	4989	22
1939-1940				+	4978	23
1952-1953		--		+	4961	24
1974-1975	-	--	---	-	4939	25
1979-1980	++			-	4654	26
1965-1966	--	----	--	-	4619	27
1935-1936	--	---		-	4519	28
1983-1984		---	++++	-	4438	29
1991-1992	++	----	++	-	4342	30
1962-1963	-		--	-	4322	31
1958-1959	++++	--	-	-	4281	32
1956-1957	++		---	+	4247	33
1966-1967	-	--	+	+	4194	34
1987-1988	-	-	++++	-	4080	35
1986-1987	--			-	4023	36
1946-1947		-		+	3954	37
1937-1938	+	-		+	3945	38
1990-1991	++	--	+	-	3811	39
1932-1933	-	-		-	3771	40
1977-1978	-	-	++	-	3577	41
1943-1944	--		-	-	3404	42
1971-1972		-	---	-	3322	43
1942-1943	-			-	3276	44
1976-1977	--		-	-	3101	45
1950-1951			---	-	3042	46
1985-1986	--			-	3032	47
1964-1965	--	--	-	+	3018	48
1989-1990	+++	--	--	-	3001	49
1975-1976			---	-	2879	50
1967-1968		-	-	+	2812	51
1981-1982	++			-	2715	52
1963-1964	-		---	-	2710	53
1955-1956	-	--	---	+	2710	54
1973-1974	-	--	-	-	2681	55
1972-1973		-	+	-	2662	56
1944-1945	--	--		+	2638	57
1993-1994		+	+++	-	2618	58
1938-1939	+		-	+	2600	59
1988-1989			--	-	2572	60
1931-1932	-	--		+	2379	61
1984-1985	-	++		-	2322	62
1996-1997	--	-	-	+	2321	63
1970-1971	+	-		-	2044	64
1961-1962				+	2014	65
1980-1981	+++	--		-	1100	66

4.3 Training Period

The period of March, 1933 through March 1988 was selected as the training period. The results of two sectors of the training period are illustrated in Figure 2. The lower half of these plots illustrate the predicted inflow and the actual inflow versus time. The right axis is the scale that represents the inflow volumes. The repetitive lines near the top of the plots represent the levels that special operations may be needed to lower water levels for flood protection. When water levels reach the upper line, large discharges that have undesirable impacts to the downstream ecosystems are required. The remaining line represents the Lake water level with the current operational schedule. The available water for water supply is very limited when the Lake water level falls below 3 meters relative to National Geodetic Vertical Datum (NGVD). This vertical datum was adopted by the United States in 1929 and is synonym for the 1929 local mean sea level datum.

The ability of this configuration of the neural network to recognize patterns of solar and global indices is demonstrated. The drought periods that are acknowledged by water managers in south Florida as being exceptional for Lake Okeechobee include: the mid- 1950s, the early to mid- 1960s, and extended periods of the 1970s and early 1980s. The coefficient of determination for the actual versus the predicted inflows was 0.50.

4.4 Testing Period

Figure 3 illustrate the results of the testing period. The neural network successfully predicted the drier period of 1988 and the first few months of 1989, and the very wet period of 1994 and 1995 and again the return to drier than normal conditions in 1996 and the beginning of 1997. However, it over predicted the 1990 and 1991 inflows. The 1990 over prediction of inflow was most likely caused by the persistence of the atmosphere and a strong La Nina condition that existed at that time. It is, however, a clear indicator that the drought is about to end. The over prediction for 1991 were due to depletion of the storage in the lake tributary basins. This storage had to be replenished before inflows to the Lake could be generated. The predictions made by the neural network still provide very valuable information for water managers of the

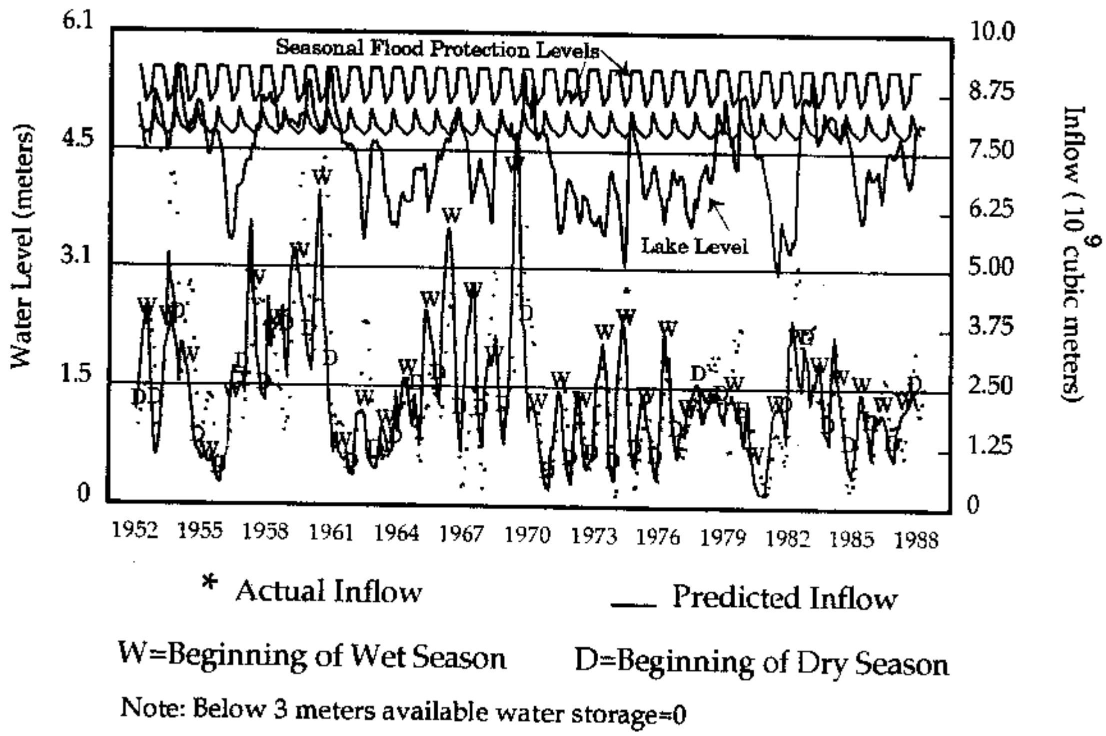


Figure 2. Lake Okeechobee Six Month Actual and Predicted Inflow - Training Period

changing state of the climate. It signaled the up coming drought when water levels were still at high levels and also signal the eventual end.

Figure 4 illustrates a scatter plot of the predicted inflows versus actual inflows for the testing period. The coefficient of determination was equal to 0.48. This is especially significant when it is considered that no regional hydrology input is included in the predictor.

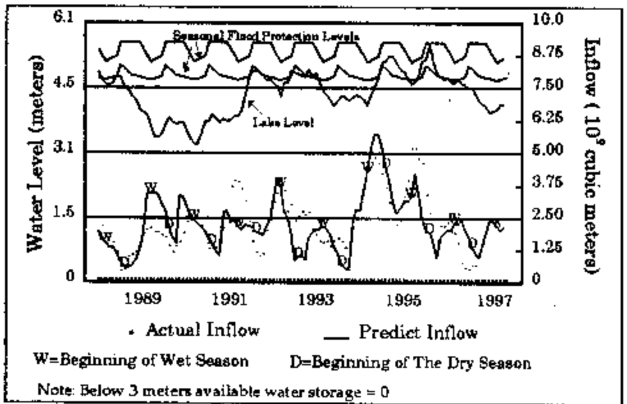


Figure 3. Lake Okeechobee Predicted and Actual 6 Month Inflow - Test Period

5. PERFORMANCE OF PROPOSED SCHEDULE

The performance of the proposed Lake Okeechobee climate-based operational schedule is compared to that of the current operational schedule with the application of the South Florida Water Management Model (SFWMM; 1997). This integrated surface water-groundwater model was designed as a tool to aid water managers in the analysis of complex regional hydrologic issues. The model domain includes a region of southern Florida that covers nearly 20000 km^2 with a mesh of 1746 cells. Lake Okeechobee is modeled separately from the grid mesh as a flat pool-lumped reservoir system. The model is a continuous simulation model with a time step of one day. Key processes simulated include: overland and groundwater flow, infiltration, percolation, canal routings, levee seepage, canal-groundwater seepage and groundwater pumpage withdrawals. Operational rules for all the major water control structures and pump stations are also simulated.

The proposed schedule is evaluated by comparing its performance to that of the current base simulation. The incorporation of the proposed schedule is the only assumption that differs in this model simulation from the 1990 base simulation. The performance measures discussed in this report include the primary measures developed for the Lower East Coast Regional Water Supply Plan. For a more detailed look at a larger set of performance measures compared with two other proposed schedules see the report entitled *Simulations of Alternative Operational Schedules for Lake Okeechobee* (Neidrauer, Trimble and Santee, 1997).

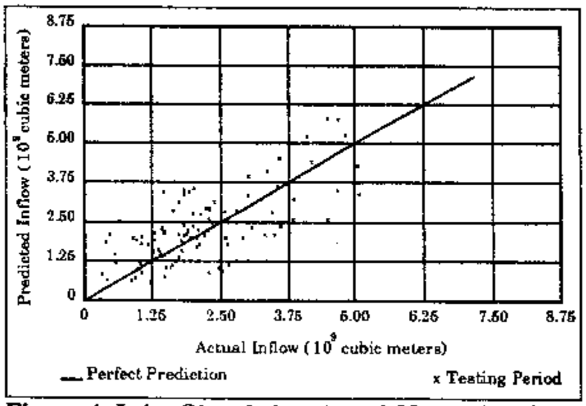


Figure 4. Lake Okeechobee Actual Versus Predicted 6 Month Inflow

Marked improvement in the proficiency of meeting the water management objectives associated with Lake Okeechobee is demonstrated with this climate based schedule. Simulated water deliveries to the Everglades natural wetlands were increased from 6 x 10^9 m^3 to 8 x 10^9 m^3 while at the same time increasing the percentage of water supply needs met by 5 percent. Delaying discharges to tide-water also minimizes the adverse effects that these discharges would have on the downstream estuaries.

6. SUMMARY

This report presents the basis for the recommendation of a Lake Okeechobee operational schedule being considered by the South Florida Water Management District for implementation. The theme of this schedule is increased operational flexibility. Operational guidelines are suggested that are not only a function of the existing system-wide hydrologic conditions but also projected Lake inflow. The inflow estimates are computed from solar, and global climate indices. Although a general hypothesis is available to describe the physical mechanism for these inflow forecast, the actual complex interaction of these processes are not well understood. The real marvel of this analysis was the computational power of artificial neural networks for recognizing patterns of climate and solar indices to produce various types of inflow events. The intent of these inflow forecasts is to provide guidance to system operators of the general state of the global climate and the potential for wet or dry extreme events. With these information it is illustrated that water management proficiency may be improved.

The recent advances that have been made in predicting solar activity for both shorter periods of a few hours (Wu et al, 1997) and to longer periods such as 11- year solar cycle (Ashmall and Moore, 1997) suggest great potential for improving climate forecast for more efficient water management.

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PREDICTING EFFECTS OF CLIMATE FLUCTUATIONS FOR WATER MANAGEMENT BY APPLYING NEURAL NETWORK

Eric Zhang and Paul Trimble
Hydrologic Systems Modeling Division
Planning Department
South Florida Water Management District
West Palm Beach, Florida 33406 USA

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SUMMARY

The ability to forecast hydrologic effect of climate fluctuations would be a valuable asset to regional water management authorities such as the South Florida Water Management District. These forecasts may provide advanced warnings of possible extended periods of deficits or surpluses of water availability allowing better regional water management for flood protection, water supply, and environmental enhancement. In order to achieve this goal, it is necessary to have a global perspective of the oceanic and atmospheric phenomena which may affect regional water resources. However, the complexity involved may hinder traditional analytical approaches in forecasting because such approaches are based on many simplified assumptions about the natural phenomena.

This paper investigates the applicability of neural networks in climate based forecasting for regional water resources management. A neural network is a computational method inspired by studies of the brain and nerve systems in biological organisms. Neural networks represent highly idealized mathematical models of our present understanding of such complex systems. Typically, a neural network consists of a set of layered processing units and weighted interconnections between the units. There exists a variety of neural network models and learning procedures. This paper applies the most widely used Back Propagation model to the climate forecasting. An advantage of applying this technique is that neural networks have the capability of self-learning, and automatic abstracting. The users do not have to know, and in many cases they do not know, the mathematical expressions of the variables involved. Neural networks learn from training data sets.

While the architecture of the Back Propagation network is fairly established, the process of determining the best suitable network configuration and the best parameters for a given application is trial-and-error, especially

when the relationships between the variables are not well understood. On the other hand, this trial-and-error process can be used to help reveal the underlining relationships between variables. In this study, issues such as selecting a best fit neural network configuration, deploying a proper training algorithm, and preprocessing input data are addressed. The effects of various global oceanic and atmospheric variables to the regional water resources are also discussed.

The study is focused on the prediction of inflow to Lake Okeechobee, the liquid heart for south Florida. Several global weather parameters over the past several decades are used as input data for training and testing. Different combinations of the variables are explored. Our preliminary results show that the neural networks are promising tools in this type of forecasting.

INTRODUCTION

Regions of south and central Florida have experienced a significant large-scale downward trend in it's wet season (May-October) rainfall in recent decades(Chin 1993). The rainfall during these months is critical for replenishing the system storage prior to the dry season which follows (November-April). The last few years since 1990 have offered a break in the decline in rainfall. However, the question arises whether this is a reversal of a trend or just a temporary reprieve. Rasmusson and Arkin (1993) did a nice job in making it clear that a global understanding of climate is needed to understand the reason and causes of local anomalies. They also summarize inter-decadal fluctuation in climate in the Sahel and India that appear to have very similar climate trends as those in South Florida. A better understanding of how local climate fluctuations in Florida are related to global climate shifts over time would be a useful tool for managing water levels of the present regional hydrologic system and for planning future water supply plans for this system. In addition, the predictability of trends in Florida's local meteorological variables caused by global climate fluctuations would undoubtedly be an important step, however small, to a better understanding of what effect global warming may have on our local climate.

The purpose of this research is to: 1) gain a better understanding of how climate fluctuations within the south and central Florida region may be related to global climate fluctuations or trees; 2) determine if decadal fluctuations in the local climate may be explained by global climate indices; and, 3) to determine, if such a relationship exists, can it be applied for more effectively managing the water levels and outflows of Lake Okeechobee. A neural network is used to test the predictability of Lake Okeechobee tributary inflows from global climate indices. The indices associated with Pacific Ocean Southern Oscillation (SOI) events and those associated with solar sunspot and global geomagnetic activity will be evaluated. The strong correlation between Florida precipitation and the El Nino-Southern Oscillation has already been

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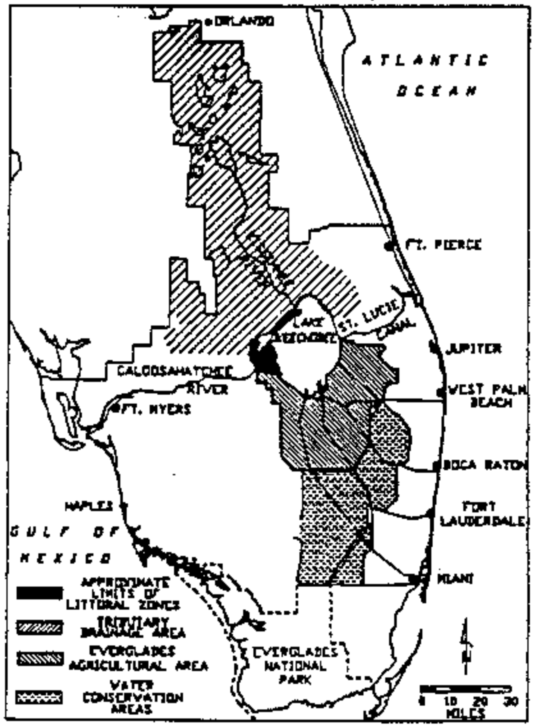

Figure 1 Location of Lake Okeechobee within South Florida Water Management District

reported (Hanson and Maul, 1991) while the solar sunspot and geomagnetic connection to climate may be more widely debated. Recent research (Labitzke and van Loon, 1989, 1992) provide us with new evidence that an important connection exist between solar cycles and the earth climate.

In this study emphasis is placed on predicting extreme high and low periods of inflow to Lake Okeechobee. Figure 1 depicts the location of Lake Okeechobee in south central Florida. Lake Okeechobee is the second largest freshwater lake lying wholly within the boundaries of the United States. This lake is frequently referred to as the "liquid heart" of south Florida as it is an important source of freshwater for many of the natural ecosystems of south Florida, the primary source of supplemental water supply for over five hundred thousand acres of intensely farmed agricultural land, and is a backup source of water supply for the densely populated urban areas of south Florida. However, south Florida's potential for periods of heavy rains and severe tropical storms and Lake Okeechobee's large tributary basins require that water levels in the lake be carefully monitored to ensure that they do not rise to levels that would threaten the structural integrity of the levee system surrounding the lake. Therefore, when water levels in the lake reach certain elevations designated by the operational schedules, discharges are made through the major outlets to control excessive buildup of water in the Lake. The timing and magnitude of these releases is not only important for preserving the flood protection of the regions, but also for protecting the natural habitats of Lake Okeechobee's littoral zone and estuaries downstream of the two major outlets. Extended periods of high water levels in the lake are stressful to the lake's littoral zone habitat, while large discharges to the estuaries cause undesirable changes to the downstream ecosystems.

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Currently the Lake Okeechobee water level and discharge operational schedule is designed to equitably meet the competing objectives of water management within the region of south Florida (Trimble and Marban, 1989). However, this operation schedule was developed based on the most recent history of water levels in the Lake and the season of the year as the reliability of long term weather forecast and the relationship between global climate and local Florida hydrology was seen as, at best, only fair. With a improved understanding of the global climate - south Florida hydrology link and the application of neural networks for climate forecasting a more dynamic operational schedule may be developed in the future that reorder operational priorities of the water management during different climate regimes. For example, during the wet periods prior to 1960 more emphasis may be put on lowering the water level in the lake to protect the lake littoral zone while during the post 1960 period more emphasis may be put on water supply since below normal rainfall threaten the ability to meet the water supply demands on the lake while the littoral zone received sufficient periods of lower water levels from lack of rainfall.

EL NINO - SOUTHERN OSCILLATION EVENT

The signature of an El Nino event is the occurrence of very warm ocean waters at low latitudes located off the west coast of South America. This region of the ocean normally has cooler sea surface temperatures due to the upwelling of the ocean.. The Southern Oscillation Index (SOI) is the measure of sea level atmospheric pressure difference between Darwin Australia (western Pacific) and Tahiti (eastern Pacific). There is a strong connection between the El Nino event and the Southern Oscillation Index. The El Nino-Southern Oscillation Event is often referred to by the acronym ENSO. An event of this type affects the climate of a large portion of the planet. The strongest and most reliable effects occur in the tropical Pacific Ocean. Other parts of the world, especially in the middle latitudes are affected through teleconnections. Teleconnections are represented as statistical associations among climatic variables separated by large distances.

Many large rainfall and drought events that occur within the state of Florida are strongly correlated to ENSO events (Hanson and Maul, 1991). This type of relationship is important to investigate farther for both operational and planning concerns. It must also be determined if ENSO events and the global teleconnections are changing as the climate changes due to global heating or the secular fluctuations of the climate. Evidence that the El Nino existed over four centuries ago is presented by Hanson and Maul (1989) and Quin, et al. (1987). Recently, Wang (1995) reported on interdecadal changes of the El Nino onset. It is vital that water managers understand what effects these changes may have on the climate of Florida. In this analysis, we assumed the SOI to be synonymous with ENSO since the period of reliable record available to us was longer than the El Nino sea surface temperature anomalies. A negative SOI index is most often associated with a warm sea surface temperature anomaly El Nino event while a positive SOI is synonymous with a cold sea surface anomaly La Nina event.

CLIMATE FLUCTUATIONS RELATED TO SOLAR SUNSPOT CYCLES

Global climate fluctuations that occur with a regular frequency may have their origins associated with solar activity. Sunspot activity displays a cyclic pattern with an approximate periodicity of 11 years. The period may actually vary between 9 and 14 years. Periods tend to be shorter when the peak of the sunspot activity is more pronounced and longer the peak is less pronounced. Between each 11-year cycle there is a reversal in the direction of the sun's magnetic field. Therefore conditions only repeat themselves every 22-years. This 22-year period is known as the Hale cycle. Willet (1975, 1987) was able to relate global climatic shifts in detail to the Hale cycle. Longer secular sunspot cycles of about 90 and 180 years were also used by Willet to explain inter-decadal changes in the global climate.

Figure 2 illustrates estimations of the relative sunspot numbers starting in the year 1750. These sunspot numbers were estimated by direct observation. Periods identified with the minimums of secular sunspot activity appear to be associated with periods of cool climates of the past. The period between 1800 and 1820 was the coldest globally since 1700. The period between 1425-1725 is believed to be the three centuries with the lowest sunspot activity of the last thousand years. This period corresponds to the period known as the Little Ice Age. In spite of some statistical evidence of a relationship between solar sunspot cycles and the earth's climate fluctuations in certain parts of the world, no completely acceptable theory has been introduced that explains how the very small changes in the energy flux that enter the earth's atmosphere due to solar cycles can be translated into climatic fluctuations. Solar Sunspots are

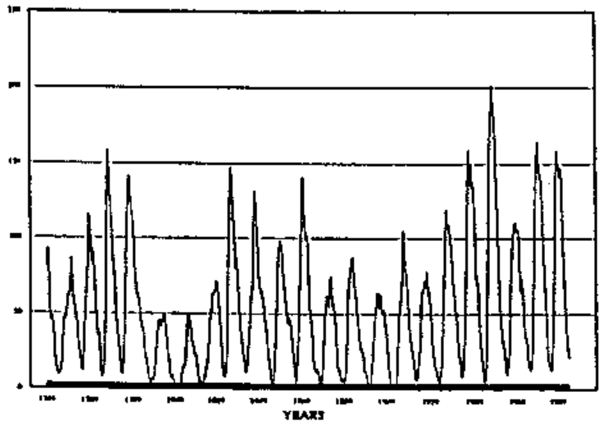

Figure 2 Relative sunspot number

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generally darker, cooler spots on the sun. However, other disturbances associated with the sunspots, such as solar flares and electromagnetic disturbances are also believed to contribute significantly to climate fluctuations. According to Willet (1953) vigorous burst of ultraviolet radiation have their greatest effects at low latitudes, leaving the polar regions fairly cold and producing a zonal pattern of general circulation. Electromagnetic disturbances on the other hand, are protons and electrons that are diverted by the earth's magnetic field toward the magnetic poles and thus heat the upper air of the polar regions more than the tropics. The zonal circulations is disrupted with a greater latitudinal transfer of air with accompanying storminess and temperature extremes. This type of activity may best be estimated by geomagnetic activity as indicated by the aa index (Willet, 1987).

The possibility of explaining a significant portion of the climate fluctuations as caused by solar activity makes it more difficult to detect anthropogenic climate trends. For example, a strong global warming trend that occurred during the period from 1920 through 1950 was suggested by some to be entirely caused by the greenhouse effect. However, this same period was also a period of larger sunspot and solar flare activity which may also be related to the global heating during this period.

HISTORY OF ENSO, SOLAR ACTIVITY, GEOMAGNETIC ACTIVITY AND LAKE OKEECHOBEE TRIBUTARY INFLOW

Figure 3 illustrates the normalized sunspot and geomagnetic activity as estimated from a six month running average of the solar sunspot number and the aa index. The period from 1930 through 1960 contains three sunspot cycles that exhibit increasing sunspot and geomagnetic activity with each cycle. The last cycle exhibits much larger activity than normal. Willet (1987) identified the period of the first three sunspot cycles as being a period of the greatest global warming within the past 500

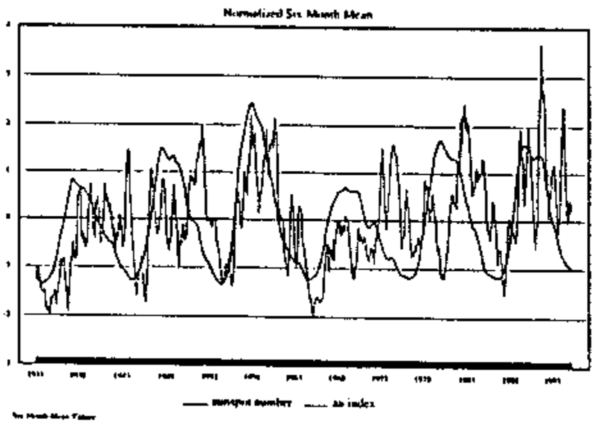

Figure 3 Sunspot number and aa index (Normalized six month mean)

years. The third sunspot cycle occurred during a period in which Lake Okeechobee received it's four largest inflow years (1957-1960). High levels of geomagnetic disturbances continued throughout this period.

The fourth sunspot cycle which lasted from 1964 until 1978 is one of minimum solar activity. Below normal rainfall and droughts were characteristic of this period. Interestingly the geomagnetic activity was delayed during this cycle so that the sunspot and geomagnetic activity were out of phase during the late 1970's and early 1980's. The minimum in geomagnetic activity associated with the minimum of sunspot activity of 1977 did not occur until the summer of 1981. This period was at the peak of 1980-1982 drought in south Florida and a time when Lake Okeechobee reached it's lowest recorded water level. Other drought periods including periods in the mid 1940's and the mid 1950's were also periods of low geomagnetic activity. This indicates that the geomagnetic activity may be an important predictor of south Florida climate. However, a period in the mid 1960's that experienced a lull in geomagnetic disturbances did not experience a similar minimum in Lake inflows. This is likely do to the ENSO event that was occurring at about the same time.

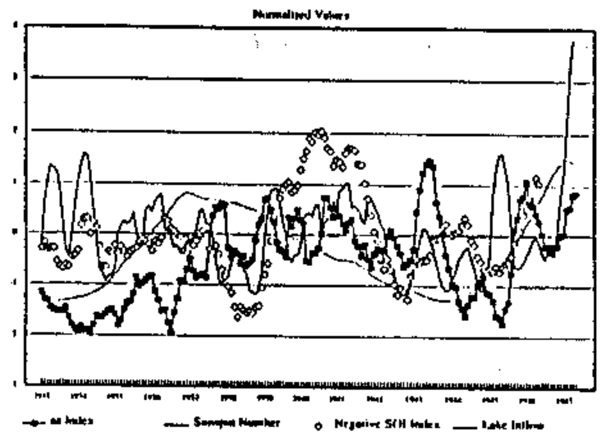

Figure 4 Lake Okeechobee inflow versus key indices - normalized values (1933-1947)

Hanson and Maul (1991) used *Superposed Epoch Analysis* to examined rainfall the years prior and during moderate to strong El Nino years. These El Nino years were defined as those events in

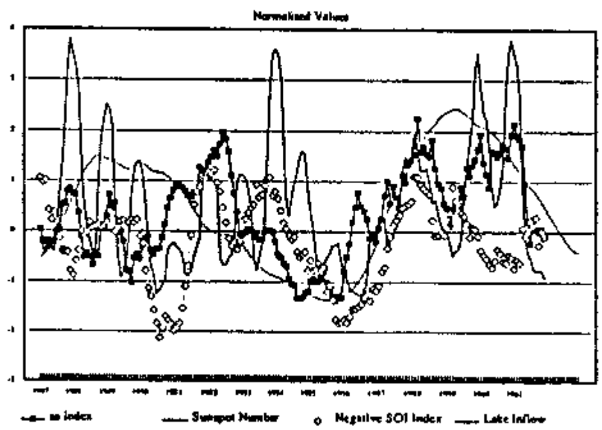

Figure 5 Lake Okeechobee inflow versus key indices - normalized values (1947-1961)

which the El Nino Event lasted 2 years or more and that the year prior to the two years must be an non-El Nino year. The years they determined were strong El Nino years within our study period included: 1939-1940, 1957-1958, 1972-1973 and 1982-1983. Their most significant findings for Florida included: 1) below normal rainfall over the entire state of Florida during the winter and spring the year prior to an El Nino event; and, 2) above normal rainfall over all the state during the winter and spring of the second year of the anomaly. The rainfall anomalies were greatest over the southern half of the state ranging between 145% to 166% of normal.

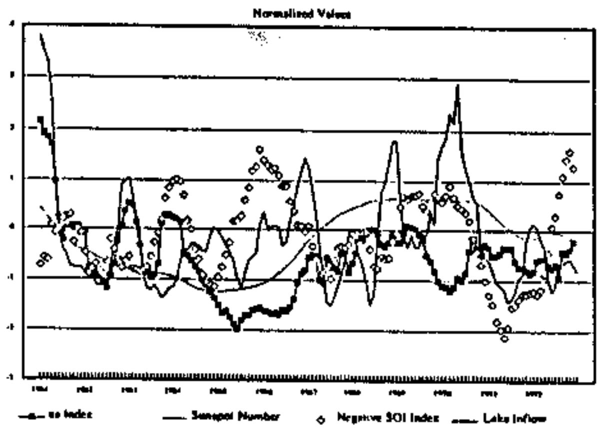

Figure 6 Lake Okeechobee inflow versus key indices - normalized values (1961-1972)

Figures 4-8 illustrate the fluctuations of the SOI, the sunspot number, and the aa index in relationship to the normalized Lake Okeechobee inflow. All lines were smoothed by a 6 month moving average and normalized by subtracting the mean value and dividing by the standard deviation. Data source for the monthly SOI was the Climate Analysis Center[1] while the monthly aa indices and sunspot number were obtained from the National Geophysical

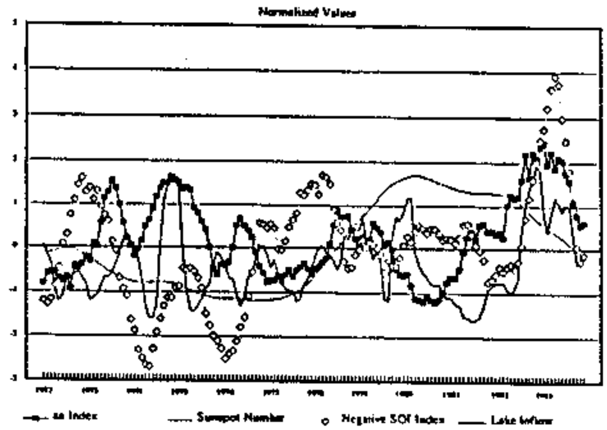

Figure 7 Lake Okeechobee inflow versus key indices - normalized values (1972-1983)

[1]Climate Analysis Center, Camp Springs, Maryland, U.S.A.

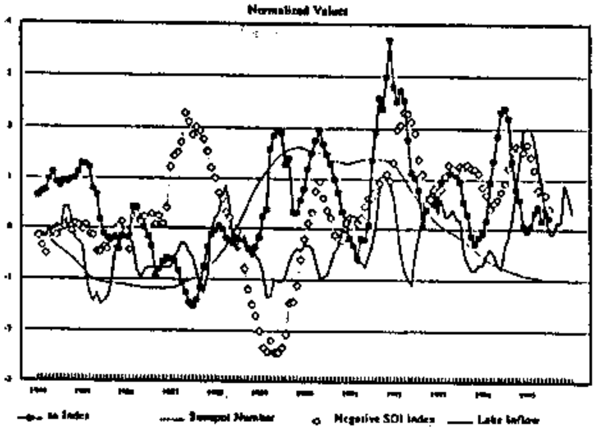

Figure 8 Lake Okeechobee inflow versus key indices - normalized values (1984-1995)

Data Center[2]. The Lake Okeechobee inflows include net rainfall on the Lake and are computed by adding historical outflows to the storage change estimated from water level fluctuations for a particular time period. Prior to 1963 the computed inflow values were obtained from the United States Army Corps of Engineers (1978). After 1963 values were computed from hydrologic data obtained from the South Florida Water Management District.

Large negative SOI values are indicative of an El Nino Event while large positive SOI values are indicative of an La Nina Event. An increase in Lake Okeechobee inflow with the El Nino-Southern Oscillation warm sea surface temperature is apparent. In fact all of the moderate and strong El Nino events reported on by Hanson and Maul and included in our period of study exhibited greater than normal Lake inflow except for the 1972-1973 El Nino events. In addition, the severe droughts of the mid 1940's, 1950's and early 1970's were marked by strong La Nina events. The effect of the 1972-1973 ENSO event was likely counteracted by the low geomagnetic activity during the same period.

It is interesting to note that the 1959-1960 period was not accompanied by an ENSO event (see Figure 5). The geomagnetic activity, however, remained very active during this period as Lake Okeechobee received it's largest two year inflow. Two separate peaks of large inflow to the Lake appear to correspond to separate peaks in electromagnetic activity. In addition, the drought of 1980-1982 appears to be associated with a minimum in geomagnetic activity and the sunspot and geomagnetic activity being out of phase with each other (see Figure 7). Paine (1983) presented a hypothesis that would connect large anomalies in rainfall along the eastern coast of North America during this period to solar activity. A weak La Nina event occurred in 1982 that may have had the effect of prolonging this drought after the geomagnetic activity increased in early 1982. To understand

[2]National Geophysical Data Center, Boulder, Colorado, U.S.A.

the factors effecting south and central Florida climate and therefore Lake Okeechobee inflow, the geomagnetic disturbances, sunspot number and ENSO events appear to need consideration in unison. During certain periods the effects of these processes may work together to enhance the likelihood of severe floods or droughts or sometimes to work against each other to lessen the likelihood of an extreme event. In addition to the indices discussed above the suns polarity and month of the year is included as input for the neural network.

A BRIEF INTRODUCTION OF ARTIFICIAL NEURAL NETWORKS

An artificial neural network (hereafter referred as neural network or network) is a computing method inspired by structure of brains and nerve systems. A typical neural network consists of a group of inter-connected processing units which are also called neurons. Each neuron makes its independent computation based upon a weighted sum of its inputs, and passes the results to other neurons in an organized fashion. Neurons receiving input data form the input layer, while those generate output to users form the output layer. A neural network must be trained by data for a problem. The training process is to adjust the connecting weights between each neurons so that the network can generalize the features of a problem and therefore to obtain desired results.

Among other advantages when compared with analytical approaches, the neural network approach does not require human expert knowledge in terms of mathematical descriptions of the problem. A neural network is trained from training data sets. This made neural network a desirable tool in dealing with complex systems, especially those of which the analytical descriptions may yet limited while their solutions are more of concerns, such as the problem discussed in this paper. The mathematically descriptive knowledge of the relationship between the solar activities and our regional climate fluctuations are limited, while the outcome of the climate may yield significant impact on water management.

Neural networks have received attention from many professions. In water resources and hydrology, neural network has also been finding its various applications (Karunanithi, et al., 1994; Smith and Eli, 1995; Crespo and Mora, 1993; Grubert, 1995; Raman and Sunilkumar, 1995; Derr and Slutz, 1994)

BACK PROPAGATION

Among the variety of neural network paradigms, the Back-propagation is the most common in use and has been applied successfully to a broad range of areas such as speech recognition, autonomous vehicle control, pattern recognition, and image classification. Its training procedure is intuitive because of its relatively simple concept: adjust the weights to reduce the error.

Back-propagation networks' topology are usually layered, with each layer fully connected to the layer before it and the one next to it. The input to the network propagates forward from the input layer, through each intermediate layer, to the output layer, resulting in the output response. when the network corrects its connecting weights, the correction process starts with the output units and propagates backward through each intermediate layer to the input layer - hence the term Back propagation.

A typical back-propagation neural network has three or more layers of processing units, Figure 9 shows the topology for a typical three-layer network. The left most layer of the network is the input layer, the only units in the network that receive input data. The middle layer is also called hidden layer, in which the processing units are interconnected to layers right and left. The right most layer is the output layer. Each processing unit is connected to every unit in the right layer and in the left layer, but it is not connected to other units in the same layer. A back-propagation network can have one or more than one hidden layers, although many have one or two hidden layers.

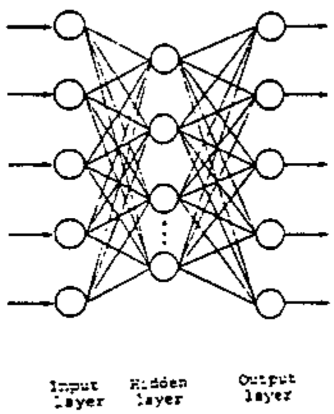

Figure 9 Schematics of a three-layer, back-propagation neural network

There are two phases in its training cycle, one to propagate the input pattern and the other to adapt the output. It is the errors that are backward propagated in the network iteration to the hidden layer(s).

A detail description of the mechanism of back-propagation neural network can be found in books in the field, such as the one by Rumelhart and MaClelland, 1986.

CHOOSING A NETWORK CONFIGURATION

The size of input layer and output layer are fixed by the number of inputs and outputs our prediction requires, i.e., 5 input layer neurons for all the five input variables, a single output neuron for the predicted change of inflow to the Lake Okeechobee. there is no universally applicable formula to be used for deciding the size of middle layers. In general, networks with too many hidden neurons tend to memorize the input patterns and may lack of generalization, while those with too few hidden neurons may not be able to simulate a complex system at all. In the former case, a network responses to the training data very well, but when presented with the data it has not seen before, it falls to generate responsive outputs. In the latter case, a network may not have sufficient dimensions to be trained for the problem and its performance may not be improved no matter how many training it received. A network with more hidden neurons also requires more computing power and more training time needed. The best way to determined the number of middle layers and their sizes is trial-and-error. This can also be helpful to reveal the underlining relationships between variables. The rule of thumb is to start with the smallest size possible for a given problem to allow for generalization, then to increase the size of the middle layer(s), until the optimal results achieved.

We experimented with both one and two hidden layer configurations, with the size ranging from 3 neurons to 11 neurons, and found the one hidden layer with 6 neurons most suitable to the problem.

INPUT DATA PREPARATION

This procedure is crucial to the success of applying neural network approach. The performance of a neural network largely depend upon the data set it was trained. in general, the better the training data sets represent the objective system, the better performance of the neural network. The preparation includes the selection of input variables, the examination of the data to eliminate bad data points, averaging, and normalizing.

The selection of input variables is solely problem dependent. After analyze the problem, five variables were chosen for this study. They are: Southern Oscillation Index (SOI), Sun Spot Number (SSN), aa-index, polarity index, and month index.

Extraneous data are not relevant to the generalization and therefore need to be carefully eliminated. All our input data were examined for eliminating spikes resulting from bad data.

Our goal is to use the information of past 6 months, including current month, to predict future 6 months inflow to the Lake Okeechobee. Therefore, a six month running averaging is applied to the raw data. All input variables were averaged for past six months, including current month, and the observed inflow data was averaged for the future 6 months. This is also necessary to further factor out local noises of the data (Derr and Slutz, 1994).

Because neurons at the middle layer fire when their input data exceeds a threshold, neural network are more responsive to a particular range of input data, it is necessary to normalize the data to the range from 0 to 1. This was done in two steps. Step one, normalizes each variable by using its respective mean and standard deviation as follows: normalized value = (original value - mean)/standard deviation; and, Step two, uses Sigmoid function to further normalize the data to the range from 0 to 1.

NETWORK TRAINING

The prepared data are 6 time series data sets, 5 for input variables and one for the target values. The duration of this time series ranging from March, 1933 to July, 1995. Each set was divided into two sections, one for training and the other for testing. An assumption on which this prediction is based is that the past data provide adequate patterns from which future events may be deduced. The duration for training data is from March 1933 through April 1987, total 650 averaged monthly data points. The duration for the testing data is from May 1987 through July 1995, total 99 data points.

All the training and testing of the neural network was done on a SPARC 20 workstation. Typical training times located between one to five hours.

RESULTS AND CONCLUSION

After training, the testing data were presented to the network to generate the prediction results. It was found that a network configuration of one hidden layer of the size of 6 neurons achieved the best prediction results as shown in Figure 10. The test data set contained a moderately severe dry period from September 1988 through May 1990 and the very wet year of 1994. The neural network was able to predict both of these events illustrating the sensitivity of south central Florida's hydrologic conditions to the global climate factors. The best global indicator of a possible drought during the 1988-1989 period was a very strong La Nina that occurred during this period. The geomagnetic activity was high during this period and appears to be out of phase with the SOI as an indicator of drought for the region (see Figure 8). This likely explains why the network did not predict as severe a drought as the one that actually occurred and might be expected by the strong La Nina event. The magnitude of the peak of the 1994 period was better predicted by the network. The predictions may

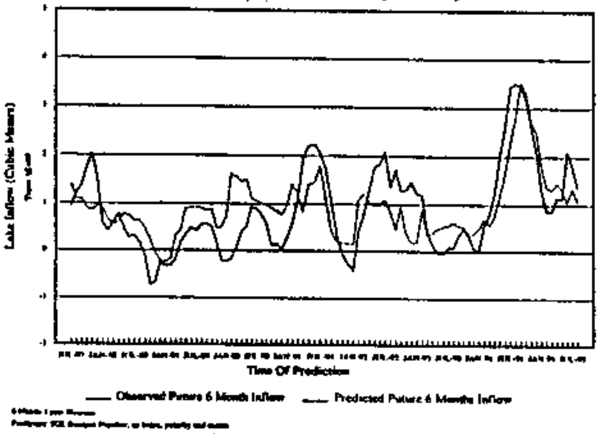

Figure 10 Lake Okeechobee predicted versus actual inflow (6 middle layer neurons - predictors: SOI, sunspot number, aa index, polarity and month)

possibly be refined by also training the neural network with trends of global indices. The predictor should be useful for operation purposes of Lake Okeechobee when used in conjunction with existing hydrologic conditions in the Lake Okeechobee tributary basins and the Lake Okeechobee water level.

The increase in geomagnetic activity in 1989 may have been a precursor of things to come. This high level of activity has continued through the 1990's. Inflows to Lake Okeechobee have returned to more normal levels as illustrated in Figure 11. There has also been an extended El Nino event that enhanced flows during this period. The last three decades have been very dry for south central Florida as indicted in this same figure. The neural network was able indicate the return to a wetter conditions.

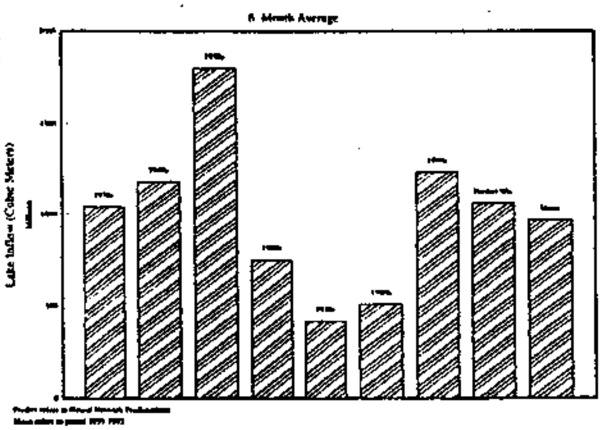

Figure 11 Decadal shifts of average inflow (predict refers to neural network predictions - mean refers to period 1933-1995)

FUTURE STUDIES

The results of this research, in addition to providing a tool for refining water management practices, leads to interesting questions. The interdecadal fluctuations of inflows to Lake Okeechobee appear to be tied to fluctuations in solar activity. How are the climate shifts due to natural fluctuations and those of a permanent shift such that might be caused by increasing the greenhouse effect isolated? Can long term solar cycles and greenhouse warming be predicted well enough so that interdecadal changes in climate can be predicted? Could this information be used to refined water management short term practices or long term plans? Can neural network technology aid in determining climate shifts?

It will be interesting to explore the neural network to predict five or ten years of Lake inflows to see if longer term climate shifts can be predicted by a neural network. In addition, experiments including other global inputs such as the Pacific-North American (PNA) index, the Quasi-Biennial Oscillation, and the North Atlantic Oscillation need to be considered. Rainfall and temperature anomalies in Florida also seem related to global

Rainfall and temperature anomalies in Florida also seem related to global rainfall and temperature anomalies and may also be considered as input to the neural network. Comparison to the predictions of traditional methods such as statistical analysis is also desirable.

ACKNOWLEDGEMENTS: Bob Hamrick's expressed concerns related to the effects of climate shifts on water resource management and his interest in the state-of-the-art computer technology helped inspire this research

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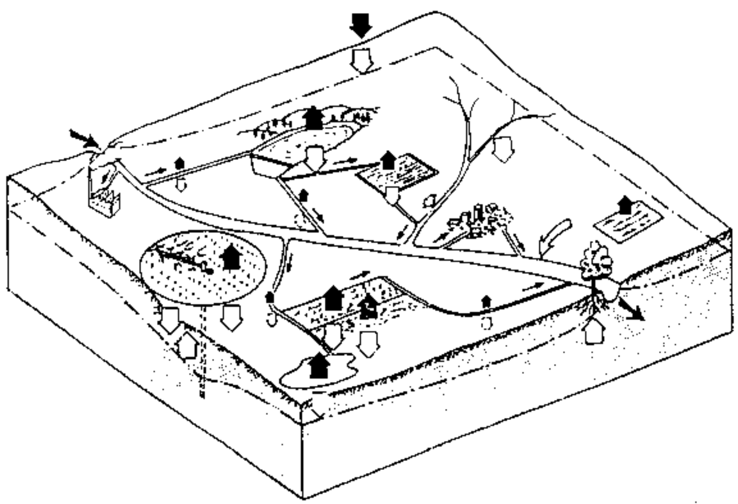
HYDROLOGY DAYS



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April 15 - April 18, 1996
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HYDROLOGY DAYS PUBLICATION

Hubert J. Morel-Seytoux

Forecasting Water Availability by Applying Neural Networks with Global and Solar Indices

Eric Y. Zhang[1], P.E. and Paul Trimble[2]

Abstract

The ability to forecast changes in water availability associated with climate fluctuations would be a valuable asset to regional water management authorities. These forecasts may provide advanced warnings of extended periods of deficits or surpluses of water availability allowing better regional water management for flood protection, water supply, and environmental enhancement.

In order to achieve this goal, it is necessary to have a global perspective of the oceanic and atmospheric phenomena which may affect regional water resources. However, the complexity involved may hinder traditional analytical approaches because such approaches are usually based upon simplified assumptions. This paper investigates the applicability of neural networks. A neural network is a computational method inspired by studies of the brain and nerve systems in biological organisms. Neural networks have the capability of self-learning and automatic abstracting. Applying this technique may reduce the time of modeling a complex system. Issues such as selecting a suitable back-propagation network configuration, and preprocessing input data are addressed.

The forecasting is focused on the inflows to Lake Okeechobee, the liquid heart of south Florida. Our preliminary results indicate that neural networks are promising tools. When the Southern Oscillation Index (SOI), the solar sunspot number and geomagnetic activity are included together as input for the neural network, the network was able to predict the largest and smallest inflow months of the testing period. Training and testing with the SOI index alone were not successful hinting at the importance of solar and/or geomagnetic activity in climate fluctuations.

Introduction

Lake Okeechobee is located in south central Florida. This body of water is the second largest freshwater lake lying wholly within the boundaries of the United States. It is frequently referred to as the "liquid heart" of south Florida as it is an important source of freshwater for many of the natural ecosystems

1&2: South Florida Water Management District, Department of Planning
3301 Gun Club Road, West Palm Beach, FL 33406

of south Florida, the primary source of supplemental water supply for over five hundred thousand acres of intensely farmed agricultural land, and is a backup source of water supply for the densely populated urban areas of south Florida. However, south Florida's potential for periods of heavy rains and severe tropical storms and Lake Okeechobee's large tributary basins require that water levels in the lake be carefully monitored to ensure that they do not rise to levels that would threaten the structural integrity of the levee system surrounding the lake.

The current operation schedule (Trimble and Marban, 1989) was developed considering only the most recent history of water levels in the Lake and the season of the year. The reliability of long term weather forecast and the relationship between global climate fluctuations and local Florida hydrology was seen as, at best, only fair. With an improved understanding of the global climate - south Florida hydrology link and the application of neural networks for hydrologic forecasting, the possibility may exist for a more dynamic operational schedule to be developed that reorder operational priorities of the water management during different climate regimes. Rasmusson and Arkin (1993) did a commendable job in making it clear that a global understanding of climate is needed to understand the reason and causes of local anomalies. They also summarized interdecadal fluctuation in rainfall in the Sahel and India that appear to have very similar trends as those in South Florida.

The purpose of this research is to: 1) gain a better understanding of how climate fluctuations within the south and central Florida region may be related to global climate fluctuations or trends, 2) determine if interdecadal fluctuations in the local climate may be explained by global climate indices, and 3) to determine, if such a relationship exists, can it be applied for more effectively managing the water levels and outflows of Lake Okeechobee. A neural network is applied to test the predictability of Lake Okeechobee inflows from global climate indices.

El Nino - Southern Oscillation Event

The signature of an El Nino event is the occurrence of very warm ocean waters at low latitudes located off the west coast of South America. The Southern Oscillation Index (SOI) is the measure of sea level atmospheric pressure difference between Darwin Australia (western Pacific) and Tahiti (eastern Pacific).

There is a strong connection between the El Nino event and the Southern Oscillation Index. The El Nino-Southern Oscillation Event is often referred to by the acronym ENSO. An event of this type affects the climate of a large portion of the planet. The strongest and most reliable effects occur in the tropical Pacific Ocean. Other parts of the world, especially in the middle latitudes are affected through teleconnections. A negative SOI index is most often associated with a warm sea surface temperature anomaly El Nino event

while a positive SOI is synonymous with a cold sea surface anomaly La Nina event.

Teleconnections are represented as statistical associations among climatic variables separated by large distances. Many large rainfall and drought events that occur within the state of Florida are strongly correlated to ENSO events (Hanson and Maul, 1991). This type of relationship is important to investigate farther for both operational and planning concerns. It must also be determined if ENSO events and the global teleconnections are changing as the climate changes due to global heating or the secular fluctuations of the climate.

Evidence that the El Nino existed over four centuries ago is presented by Hanson and Maul (1989) and by Quin et al (1987). Recently, Wang (1995) reported on interdecadal changes of the El Nino onset. It is vital that water managers understand what effects these changes may have on the climate of Florida. In this analysis, we assumed the SOI to be synonymous with ENSO since the period of reliable record available to us was longer than the El Nino sea surface temperature anomalies.

Climate Fluctuations Related To Solar Sunspot Cycles

Global climate fluctuations that occur with a regular frequency may have their origins associated with solar activity. Sunspot activity displays a cyclic pattern with an approximate periodicity of 11 years. The period may actually vary between 9 and 14 years. Periods tend to be shorter when the peak of the sunspot activity is more pronounced and longer the peak is less pronounced. Between each 11-year cycle there is a reversal in the direction of the sun's magnetic field. Therefore conditions only repeat themselves every 22-years. The 22-year period is known as the Hale cycle.

In spite of some statistical evidence of a relationship between solar sunspot cycles and the earth's climate fluctuations in certain parts of the world, no completely acceptable theory has been introduced that explains how the very small changes in the ultra-violet energy flux across the outer bounds of the earth's atmosphere due to sunspot cycles can be translated into climatic fluctuations. Willet (1953, 1987) has elaborated that solar flare activity may cause geomagnetic disturbances and strong spot heating that disrupt the zonal weather circulations. This would allow such activity to contribute significantly to climate fluctuations without appreciable changes in energy flux. The aa index of geomagnetic activity was taken by Willet to be the best indicator of solar flare activity. Recent research (Labitzke and van Loon 1989, 1992, 1993) provide additional new evidence that an important connection exist between solar cycles and the earth climate. Enfield and Cid (1991) and Mendoza et al (1991), report on possible connections between solar activity and El Nino's, while Reid and Gage (1988) and Reid (1989) reported on the similarities between the 11-year running means of monthly sunspot numbers and the global sea surface temperature.

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History of ENSO, Solar Activity, Geomagnetic Activity and Lake Okeechobee Tributary Inflow

The period from 1930 through 1960 contains three sunspot cycles that exhibit increasing sunspot and geomagnetic activity with each cycle. The last cycle exhibits much larger activity than normal. Willet (1987) identified the period of the first three sunspot cycles as being a period of the greatest global warming within the past 500 years. The third sunspot cycle occurred during a period in which Lake Okeechobee received four of the largest inflow years (1957-1960). High levels of geomagnetic disturbances continued throughout this period.

The fourth sunspot cycle which lasted from 1964 until 1978 is one of lesser solar activity. Below normal rainfall and droughts were characteristic of this period in central and southern Florida. Interestingly the geomagnetic activity was delayed during this cycle so the minimum in geomagnetic activity associated with the sunspot minimum of 1977 did not occur until the summer of 1980 and appears to be a precursor of the 1980-1982 drought in south Florida. Lake Okeechobee reached it's lowest recorded water level in July, 1981.

Other extended dry periods including the mid 1940's and the mid 1950's were also periods of low geomagnetic activity which indicates that this activity may be linked to the south Florida climate. Paine (1983) presented a hypothesis that would connect large anomalies in rainfall along the eastern coast of North America during this period to solar activity.

Hanson and Maul (1991) used *Superposed Epoch Analysis* to examined rainfall the years prior and during moderate to strong El Nino years. These El Nino years were defined as those events in which the El Nino Event lasted 2 years or more and that the year prior to the two years must be an non-El Nino year. The years they determined were strong El Nino years within our study period included: 1939-1940, 1957-1958, 1972-1973 and 1982-1983. Their most significant findings for Florida included: 1) below normal rainfall over the entire state of Florida during the winter and spring the year prior to an El Nino event, 2) above normal rainfall over all the state during the winter and spring of the second year of the anomaly. The rainfall anomalies were greatest over the southern half of the state ranging between 145% to 166% of normal.

It is interesting to note that the 1959-1960 period was not accompanied by an ENSO event. The geomagnetic activity, however, remained very active during this period as Lake Okeechobee received it's largest two year inflow. Two separate peaks of large inflow to the Lake appear to correspond to separate peaks in geomagnetic activity. To understand the factors effecting the south and central Florida climate and therefore Lake Okeechobee inflow, the geomagnetic disturbances, sunspot number and ENSO events appear to need consideration in unison. During certain periods the effects of these processes

may work together to enhance the likelihood of severe floods or droughts or sometimes to work against each other to lessen the likelihood of an extreme event. In addition to the indices discussed above the suns polarity and month of the year is included as input for the neural network.

A brief Introduction of Artificial Neural Networks

An artificial neural network (hereafter referred as neural network or network) is a computing method inspired by structure of brains and nerve systems. A typical neural network consists of a group of inter-connected processing units which are also called neurons. Each neuron makes its independent computation based upon a weighted sum of its inputs, and passes the results to other neurons in an organized fashion. Neurons receiving input data form the input layer, while those generate output to users form the output layer. A neural network must be trained by data for a problem. The training process is to adjust the connecting weights between each neurons so that the network can generalize the features of a problem and therefore to obtain desired results.

Among other advantages when compared with analytical approaches, the neural network approach does not require human expert knowledge in terms of mathematical descriptions of the problem. A neural network is trained from training data sets. This made neural network an appealing tool in dealing with complex systems, especially those of which the analytical descriptions may yet limited while their solutions are more of concerns, such as the problem discussed in this paper. The mathematically descriptive knowledge of the relationship between the solar activities and our regional climate fluctuations are limited, while the outcome of the climate may yield significant impact on water management.

Neural networks have received attention from many professions. In water resources and hydrology, neural network has also been finding its various applications (Karunanithi et al. 1994; Smith and Eli, 1995; Crespo and Mora, 1993; Grubert, 1995; Raman and Sunilkumar, 1995; Derr and Slutz, 1994)

Back Propagation

Among the variety of neural network paradigms, the Back-propagation is the most common in use and has been applied successfully to a broad range of areas such as speech recognition, autonomous vehicle control, pattern recognition, and image classification. Its training procedure is intuitive because of its relatively simple concept: adjust the weights to reduce the error.

Back-propagation networks' topology are usually layered, with each layer fully connected to the layer before it and the one next to it. The input to the network propagates forward from the input layer, through each intermediate layer, to the output layer, resulting in the output response. when the network corrects its connecting weights, the correction process starts with the output units and propagates backward through each intermediate layer to the input layer - hence the term Back propagation.

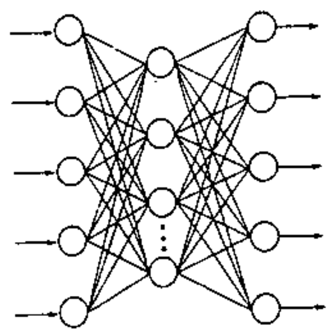

Figure 1 Schematics of a three layer back-propagatin neural network

A typical back-propagation neural network has three or more layers of processing units, Figure 1 shows the topology for a typical three-layer network. The left most layer of the network is the input layer, the only units in the network that receive input data. The middle layer is also called hidden layer, in which the processing units are interconnected to layers right and left. The right most layer is the output layer. Each processing unit is connected to every unit in the right layer and in the left layer, but it is not connected to other units in the same layer. A back-propagation network can have one or more than one hidden layers, althou~h many have one or two hidden layers.

There are two phases in its training cycle, one to propagate the input pattern and the other to adapt the output. It is the errors that are backward propagated in the network iteration to the hidden layer(s).

A detail description of the mechanism of back-propagation neural network can be found in books in the field, such as the one by Rumelhart and MaClelland, 1986.

Choosing a Network Configuration

The size of input layer and output layer are fixed by the number of inputs and outputs our prediction requires, i.e. 5 input layer neurons for all the five input variables, a single output neuron for the predicted change of inflow to the Lake Okeechobee. there is no universally applicable formula to be used for deciding the size of middle layers. In general, networks with too many hidden

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neurons tend to memorize the input patterns and may lack of generalization, while those with too few hidden neurons may not be able to simulate a complex system at all. In the former case, a network responses to the training data very well, but when presented with the data it has not seen before, it falls to generate responsive outputs. In the latter case, a network may not have sufficient dimensions to be trained for the problem and its performance may not be improved no matter how many training it received. A network with more hidden neurons also requires more computing power and more training time needed. The best way to determined the number of middle layers and their sizes is trial-and-error. This can also be helpful to reveal the underlining relationships between variables. The rule of thumb is to start with the smallest size possible for a given problem to allow for generalization, then to increase the size of the middle layer(s), until the optimal results achieved.

We experimented with both one and two hidden layer configurations, with the size ranging from 3 neurons to 11 neurons, and found the one hidden layer with 6 neurons most suitable to the problem.

Input Data Preparation

This procedure is crucial to the success of applying neural network approach. The performance of a neural network largely depend upon the data set it was trained. in general, the better the training data sets represent the objective system, the better performance of the neural network. The preparation includes the selection of input variables, the examination of the data to eliminate bad data points, averaging, and normalizing.

The selection of input variables is solely problem dependent. After analyze the problem, five variables were chosen for this study. They are: Southern Oscillation Index (SOI), Sun Spot Number (SSN), aa-index, polarity index, and month index. Data source for the monthly SOI was the Climate Analysis Center[2] while the monthly aa indices and smoothed sunspot number were obtained from the National Geophysical Data Center[3]. The Lake Okeechobee inflows include net rainfall on the Lake and are computed by adding historical outflows to the storage change estimated from water level fluctuations for a particular time period. Prior to 1963 the computed inflow values were obtained from the United States Army Corps of Engineers (1978). After 1963 values were computed from hydrologic data obtained from the South Florida Water Management District.

Our goal is to use the information of past 6 months, including current month, to predict future 6 months inflow to the Lake Okeechobee. Therefore, a six month running averaging is applied to the raw data. All input variables were averaged for past six months, including current month, and the observed

2 Climate Analysis Center, Camp Springs, Maryland
3 National Geophysical Data Center, Boulder, Colorado

inflow data was averaged for the future 6 months. This is also necessary to further factor out local noises of the data (Derr and Slutz, 1994).

Because neurons at the middle layer fire when their input data exceeds a threshold, neural network are more respo sive to a particular range of input data, it is necessary to normalize the data to the range from 0 to 1. This was done in two steps. Step one, normalize each variable by using their respective mean and standard deviation as following:

normalized value = (value - mean)/standard deviation

Step two, use Sigmoid function to further normalize the data to the range from 0 to 1.

Network Training

The prepared data are 6 time series data sets, 5 for input variables and one for the target values. The duration of this time series ranging from March, 1933 to July, 1995. Each set was divided into two sections, one for training and the other for testing. An assumption on which this prediction is based is that the past data provide adequate patterns from which future events may be deduced. The duration for training data is from March 1933 through April 1987, total 650 averaged monthly data points. The duration for the testing data is from May 1987 through July 1995, total 99 data points.

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All the training and testing of the neural network was done on a SPARC 20 workstation. Typical training times located between one to five hours.

Results And Conclusion

After training, the testing data were presented to the network to generate the forecasting results as shown in Figure 2.

The testing period contained a moderately severe dry period from September 1988 through May 1990 and the very wet year of 1994. The neural network was able to predict both of these events illustrating the sensitivity of south central Florida's hydrologic conditions to the global climate factors.

The best global indicator of a possible drought during the 1988-1989 period was a very strong La Nina that occurred during this period. The geomagnetic activity was high during this period and appeared to be out of phase with the SOI as an indicator of drought for the region. This likely explains why the network did not predict as severe a drought as the one that actually occurred and might be expected by the strong La Nina event. The magnitude of the peak of the 1994 period was better predicted by the network.

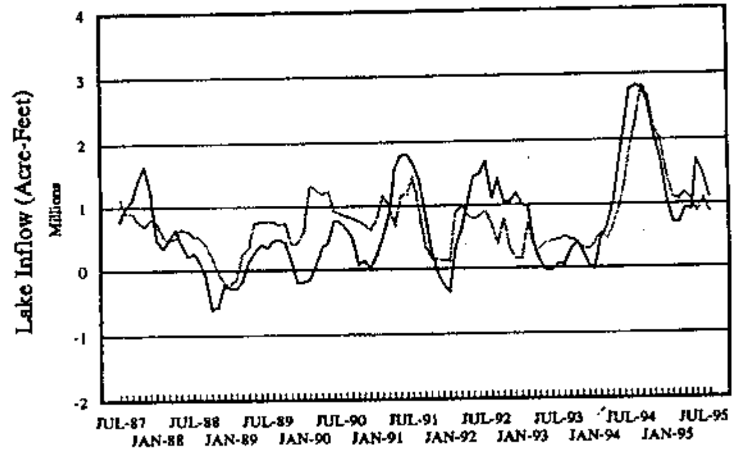

Figure 2. Predicted versus actual Lake Okeechobee inflow

Experiments attempting to train the neural network with only the SOI failed. This seemed somewhat surprising at first since the two extreme events of the period seemed adequately explained by ENSO alone. However, two of the wettest (1959-1960) and driest (1980-1981) periods on records and several other episodes during the training periods could not be explained in terms of the ENSO.

The increase in geomagnetic activity in 1989 may have been a precursor of things to come. This high level of activity has continued through the 1990s. Inflows to Lake Okeechobee have returned to more normal levels as illustrated in Figure 3. There has also been an extended El Nino event that enhanced flows during this period. The last three decades have been very dry for southern and central Florida as indicted in this same Figure. The neural network was able to indicate the return to a wetter conditions.

The predictor should be useful for operation purposes of Lake Okeechobee when used in conjunction with existing hydrologic conditions in the Lake Okeechobee tributary basins and the Lake Okeechobee water level.

Future Studies

Experiments including other global inputs such as the Pacific-North American (PNA) index, the Quasi-Biennial Oscillation, and the North Atlantic Oscillation and local antecedent hydrologic conditions need to be considered. The forecasting may be improved by also training the neural network with trends of global indices. Comparison to the predictions of traditional methods such as statistical analysis is also desirable.

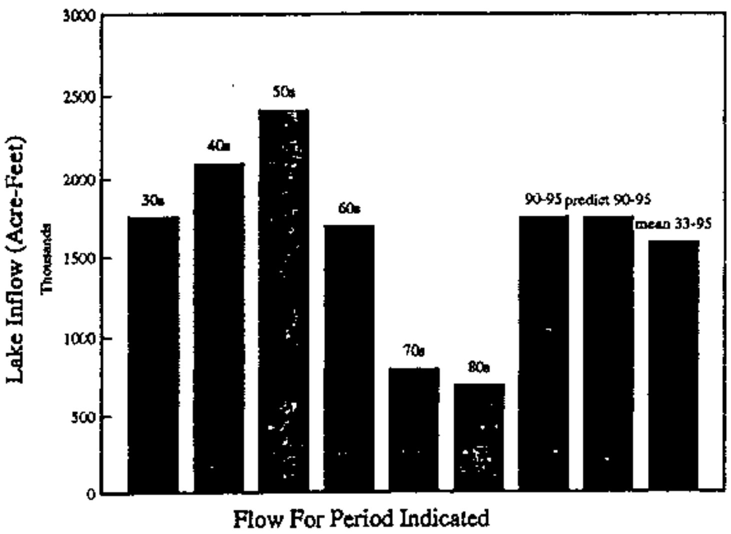

Figure 3. Decadal shfits of average annual inflow

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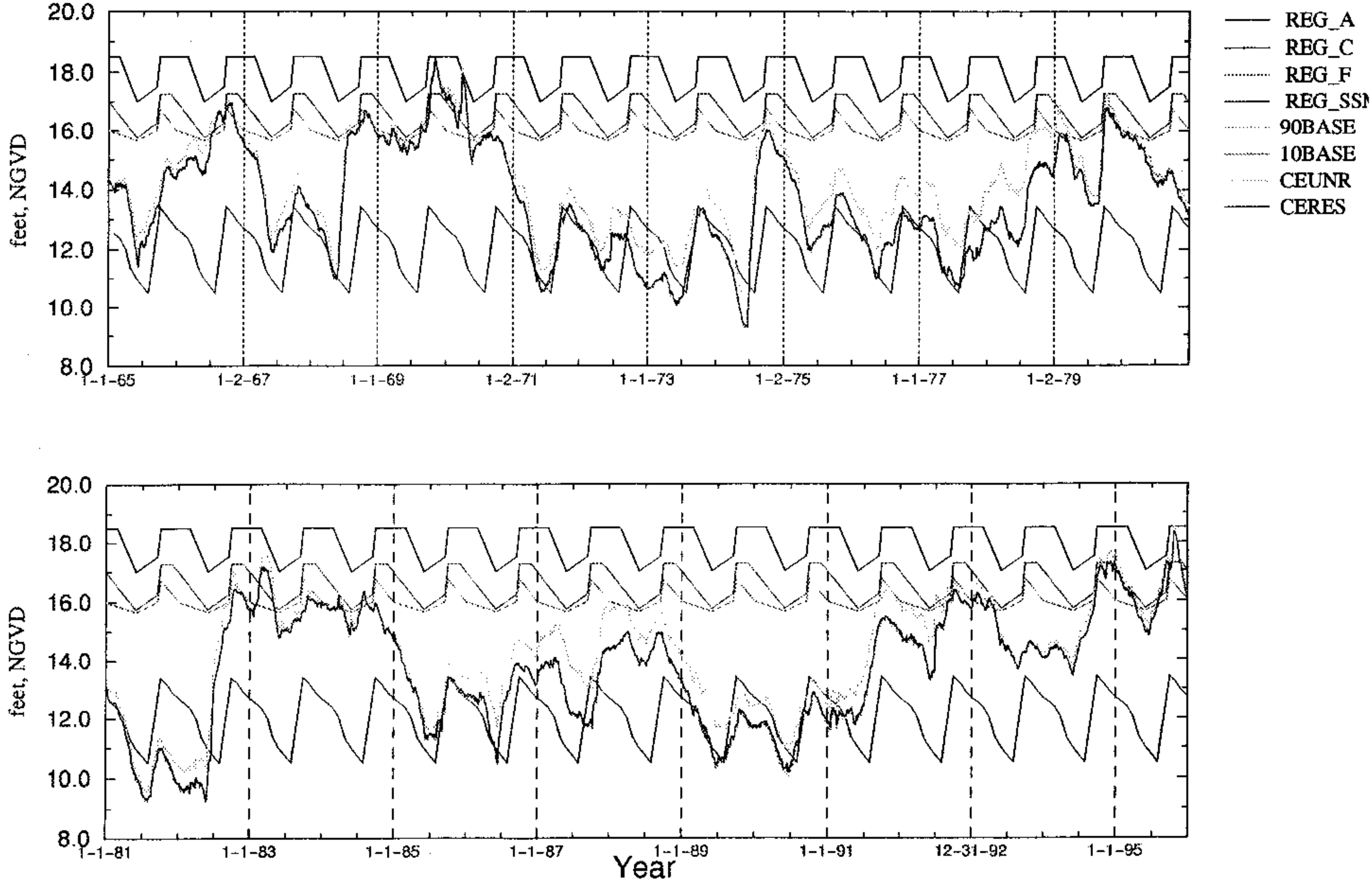
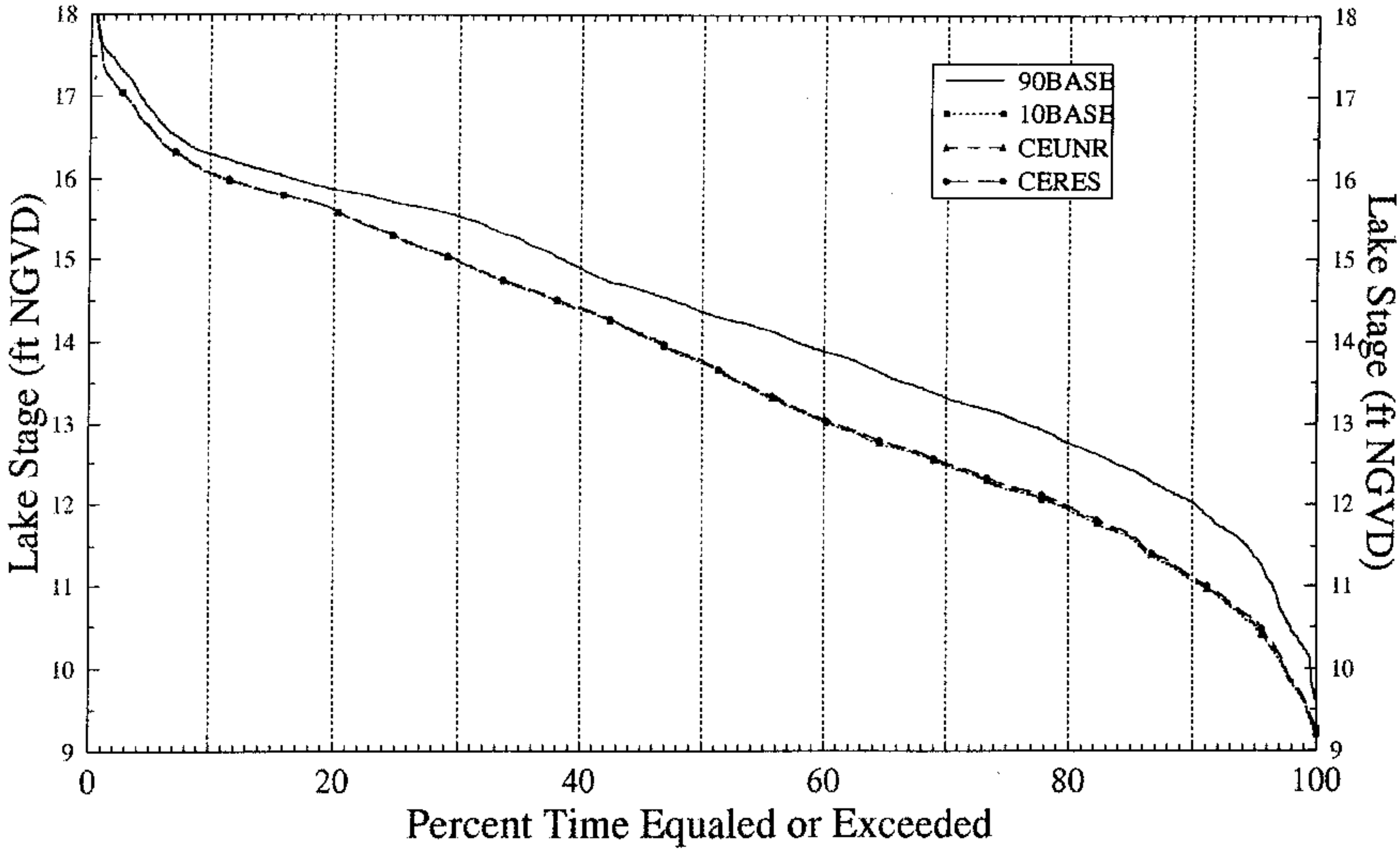
APPENDIX B. Sensitivity Analysis Results - 2010 Demand Projections

Daily Stage Hydrographs for Lake Okeechobee

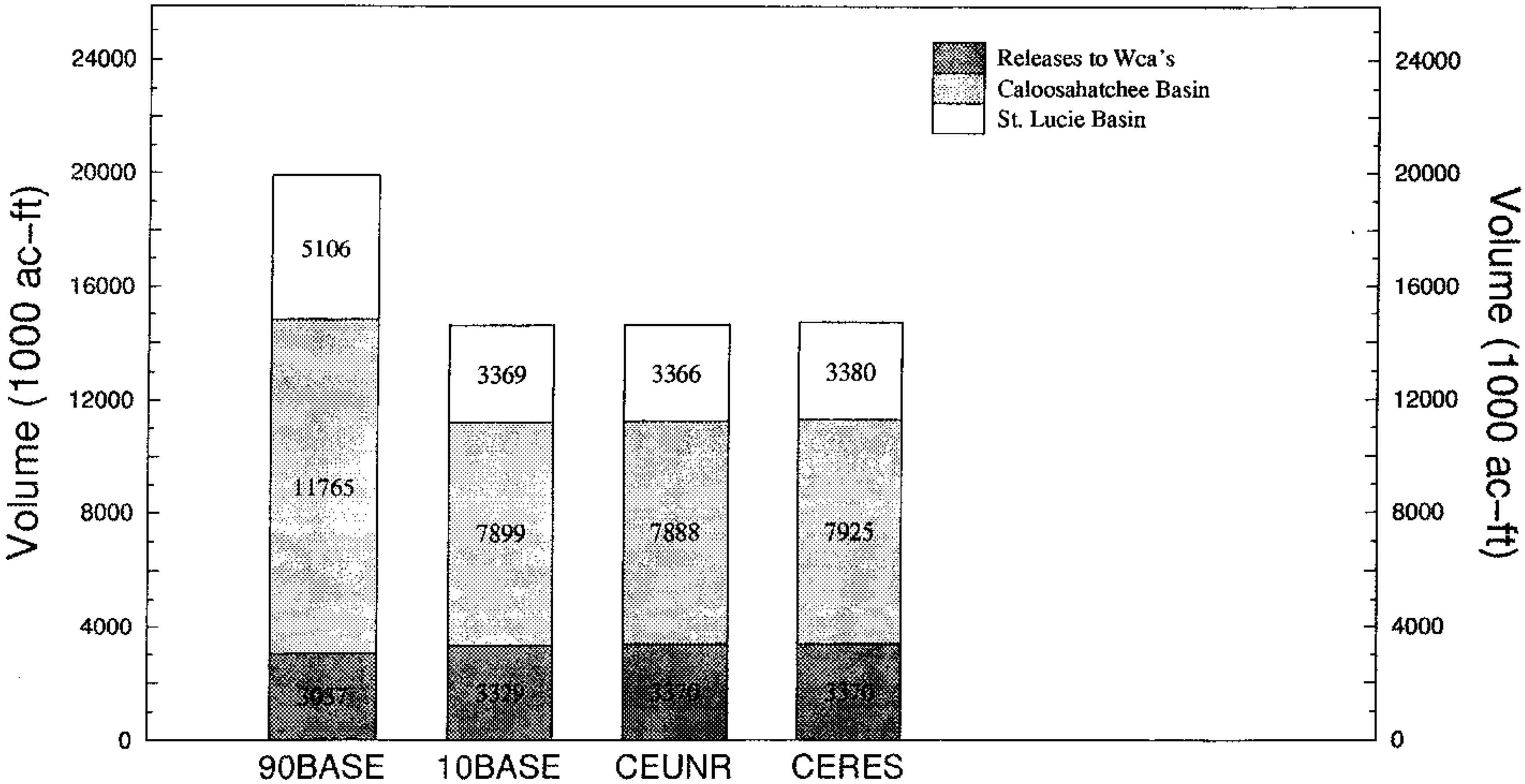


SFWMM Simulation

Lake Okeechobee Stage Duration Curves



Total Flood Control Releases from Lake Okeechobee for the 31 yr (1965 – 1995) Simulation



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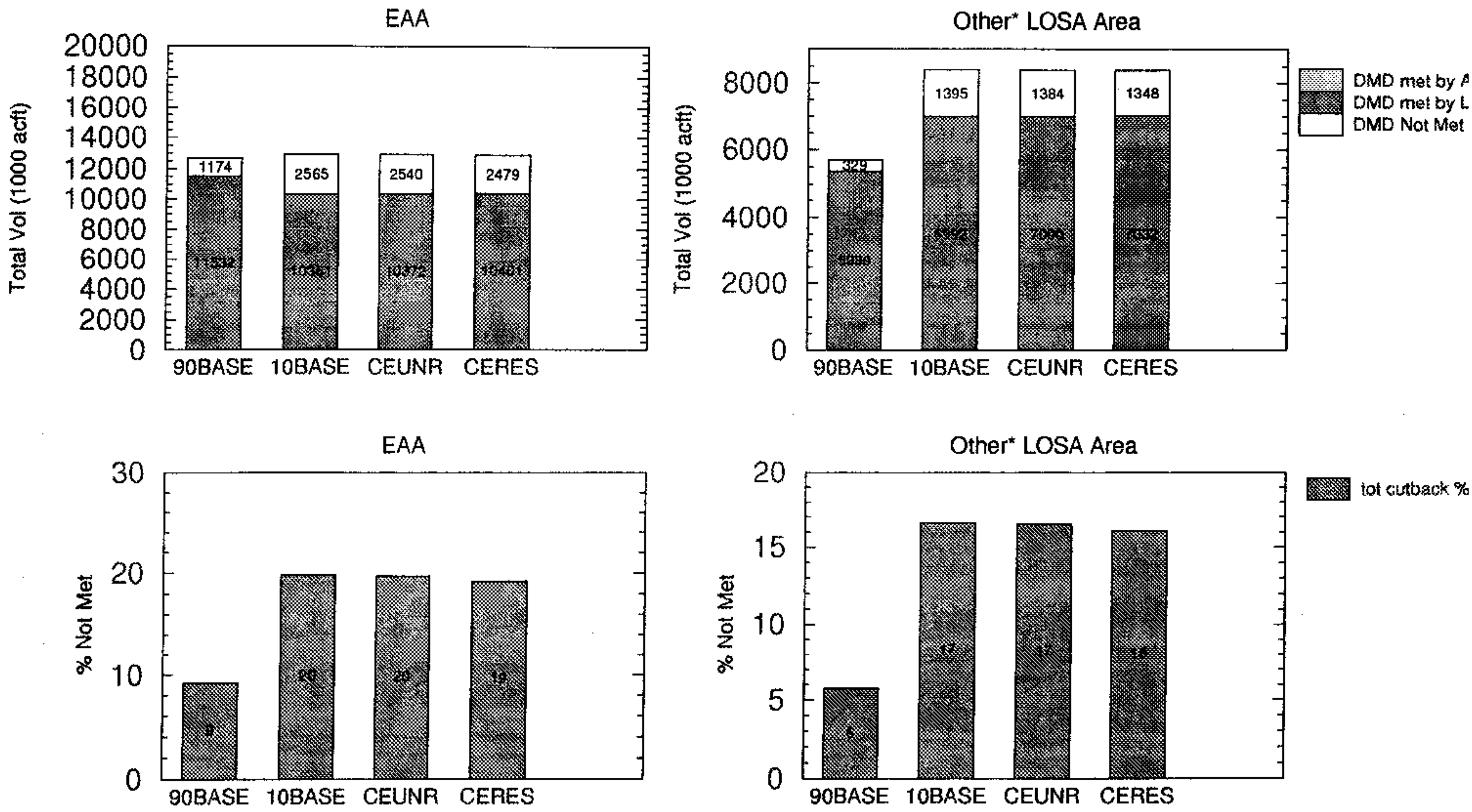
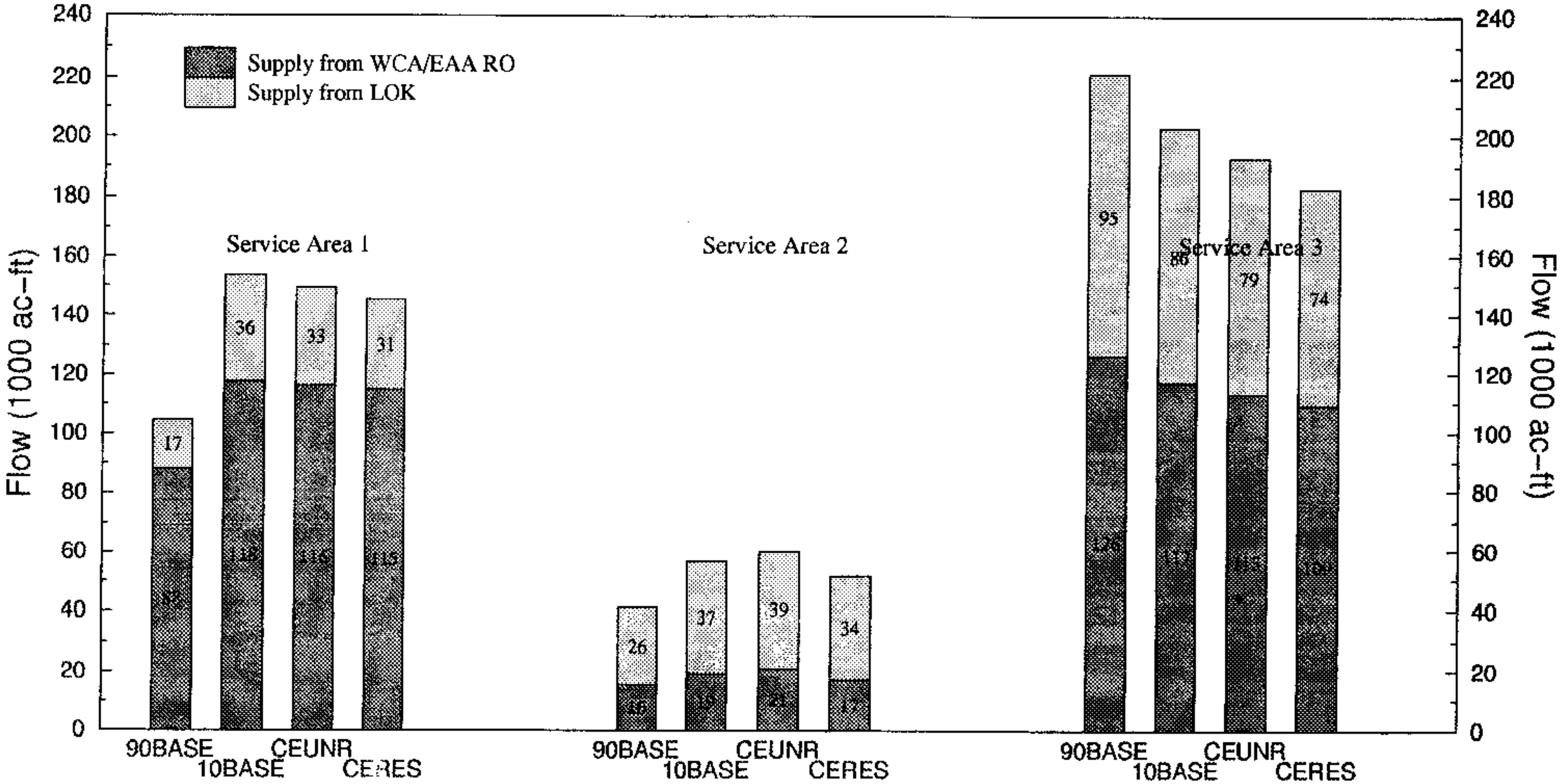
Total EAA/LOSA Irrigation Demands and Demands Not Met

for the 1965 – 1995 Simulation Period



*Other Lake Service SubAreas Outside the Plan Boundaries (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

Mean Annual Regional System Water Supply Deliveries to LEC Service Areas for the five Drought years (71,75,81,85,89)



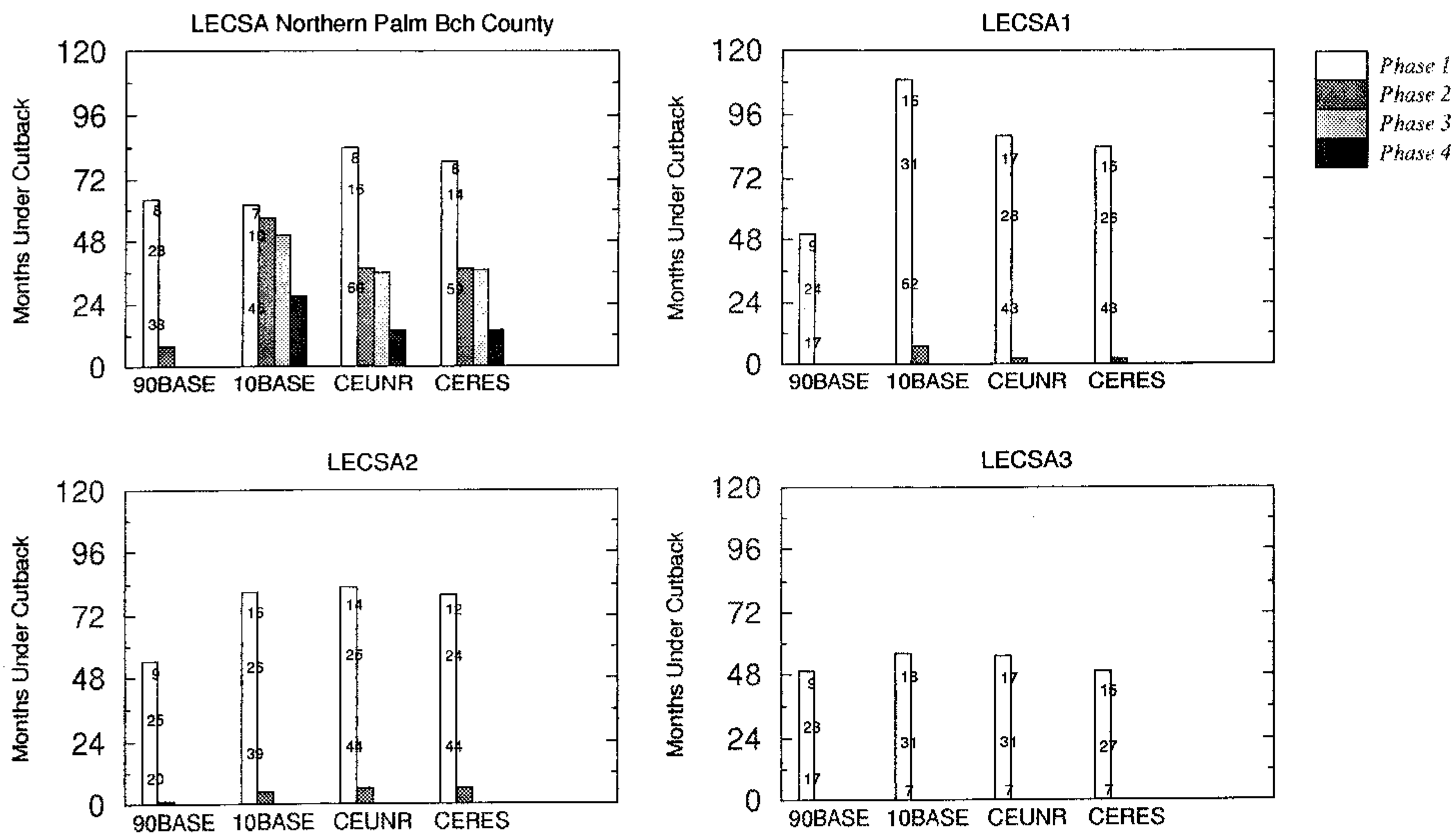
Note: Structure flows included: SA1=S39+LWDD+ADDSLW+ACMEWS+WSL8S; SA2=S38+S34; SA3=S31+S334+S337
Supply RECEIVED from LOK may be less than what is DELIVERED at LOK due to conveyance constraints.

Water Supply, Level I, LECSA1/2/3

B-6

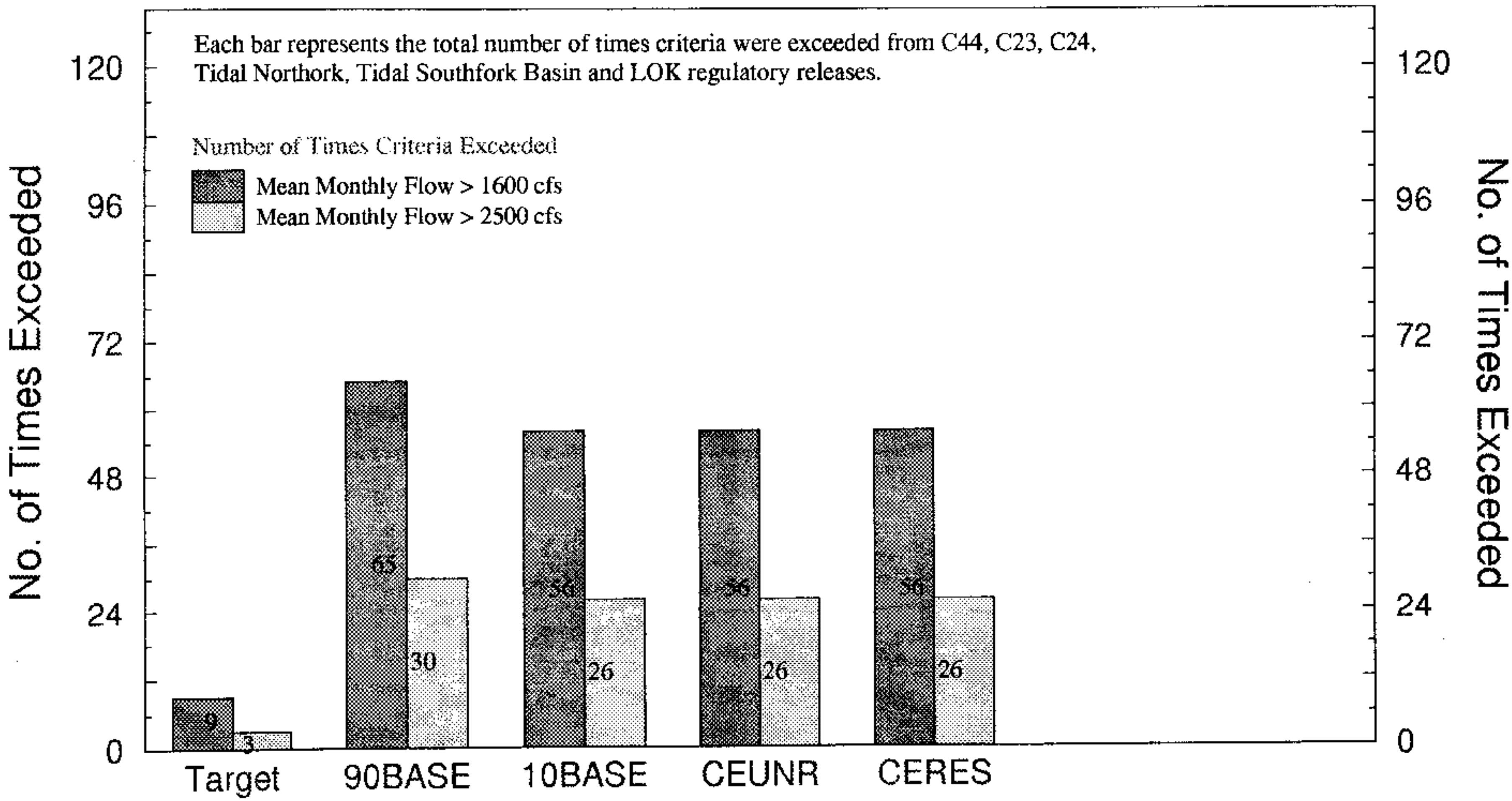
Number of Months of Simulated Water Supply Cutbacks

for the 1965 – 1995 Simulation Period



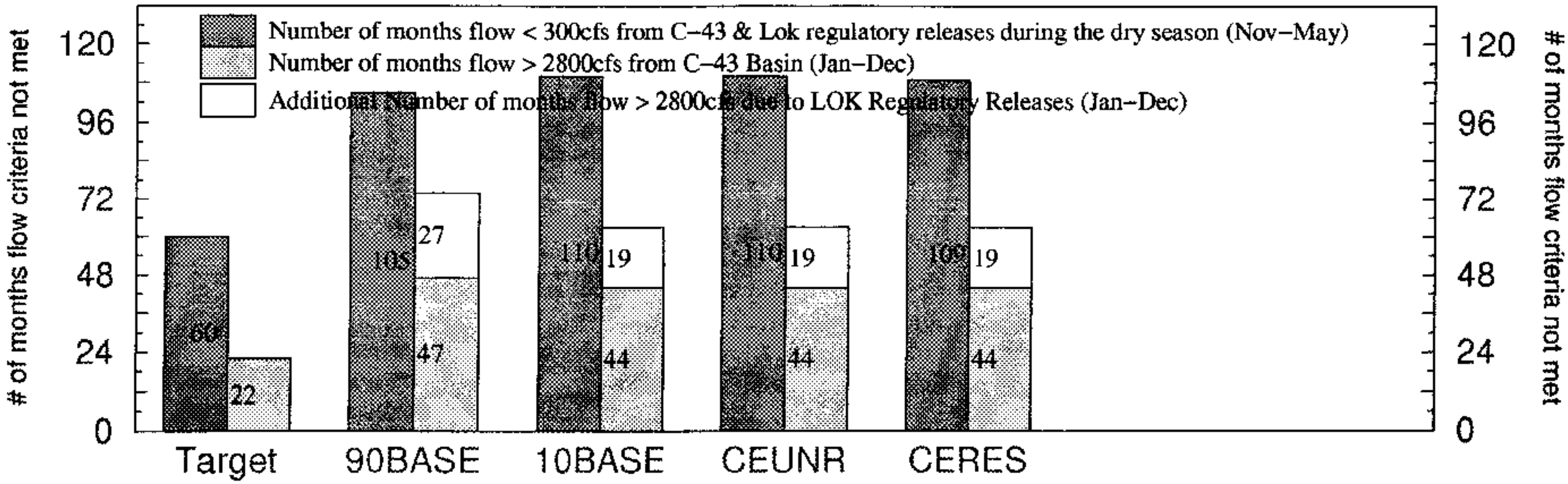
Note: Phase 1 water restrictions could be induced by a) Lake stage in Supply Side Management Zone (indicated by upper data label), b) Local Trigger well stages (lower data label), and c) Dry season criteria (indicated by middle data label).

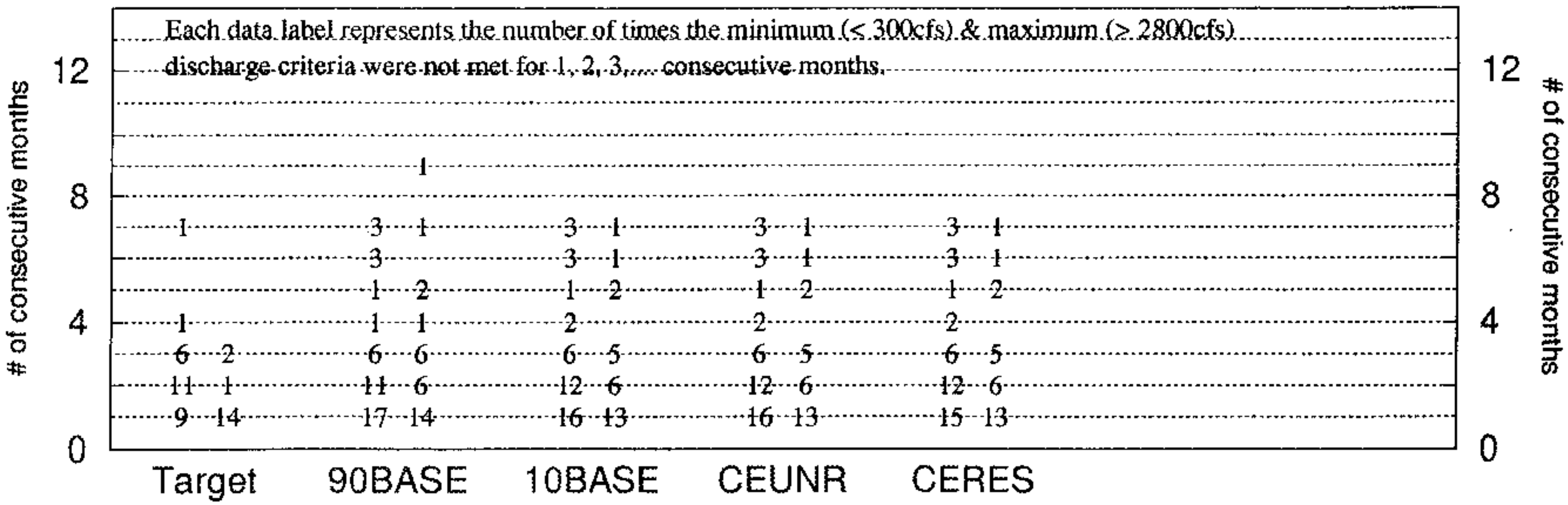
Number of Times High Discharge Criteria (mean monthly flows > 1600 & 2500 cfs) were exceeded for the St. Lucie Estuary



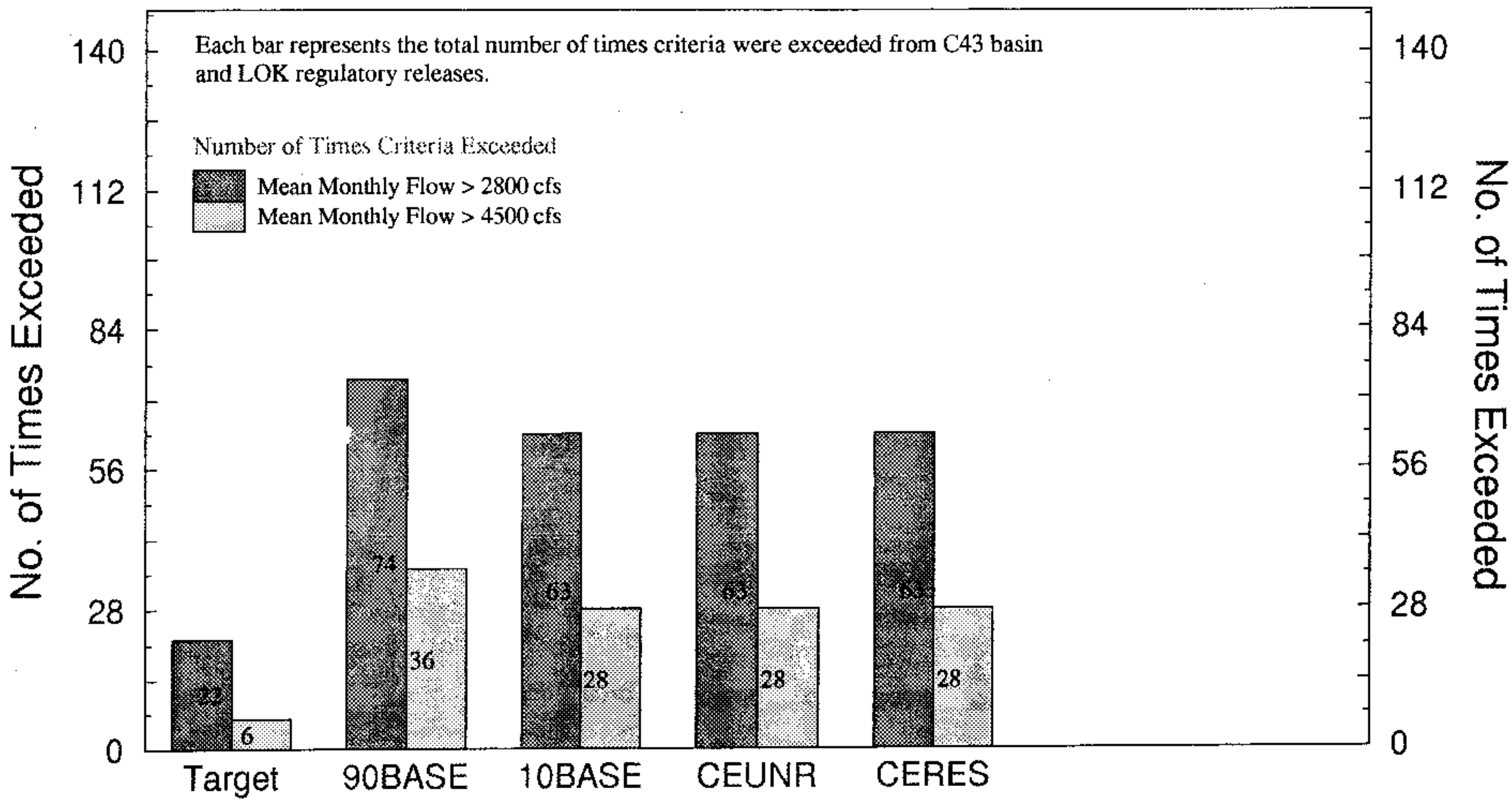
Note: A favorable maximum monthly flow was developed for the estuary (1600 cfs) that will theoretically provide suitable salinity conditions which promote the development of important benthic communities (eg. oysters & shoalgrass). Mean monthly flows above 2500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota.

Number of times Salinity Envelope Criteria were NOT met for the Caloosahatchee Estuary (mean monthly flows 1965 – 1995)

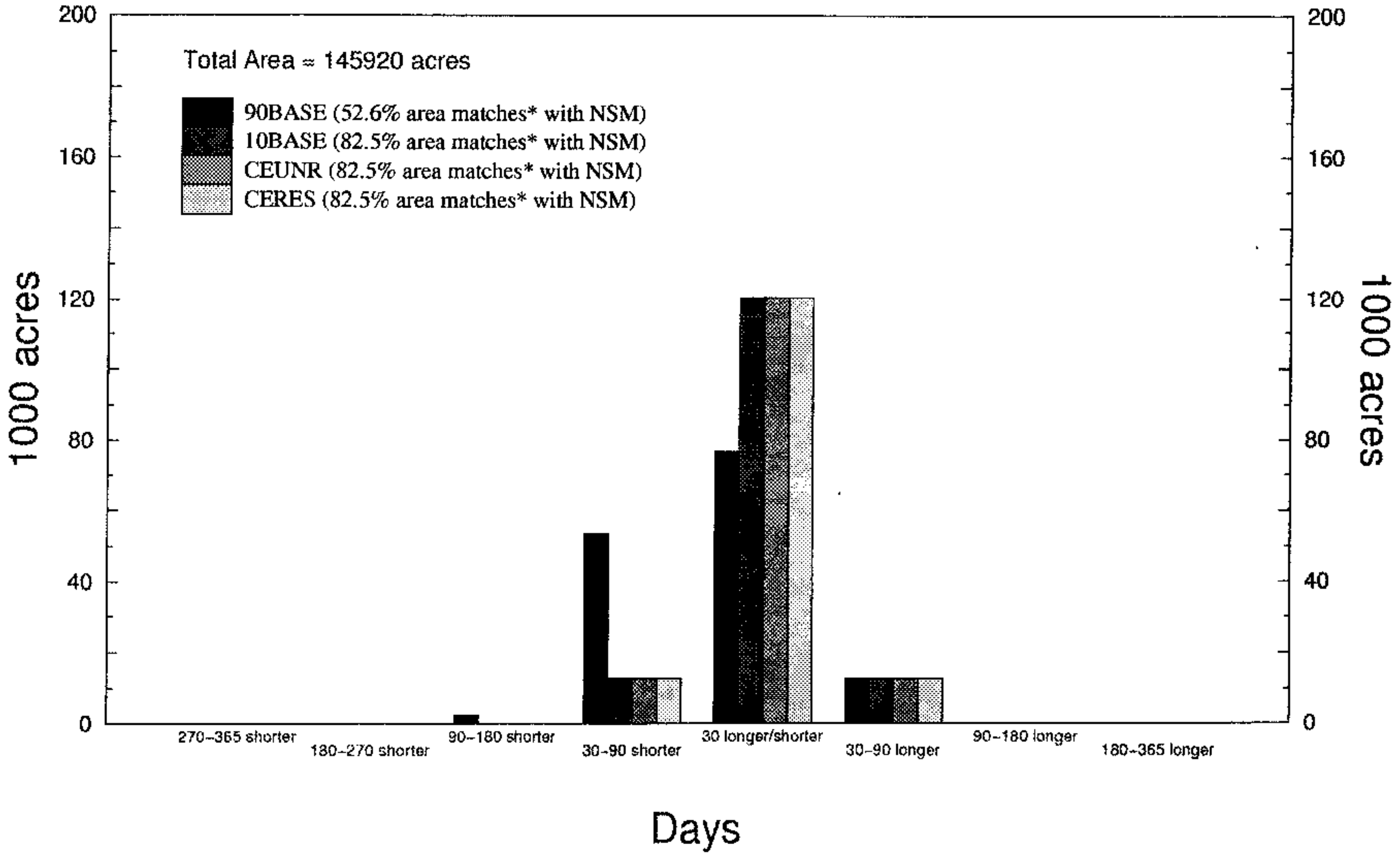




Number of Times High Discharge Criteria (mean monthly flows > 2800 & 4500 cfs) were exceeded for the Caloosahatchee Estuary

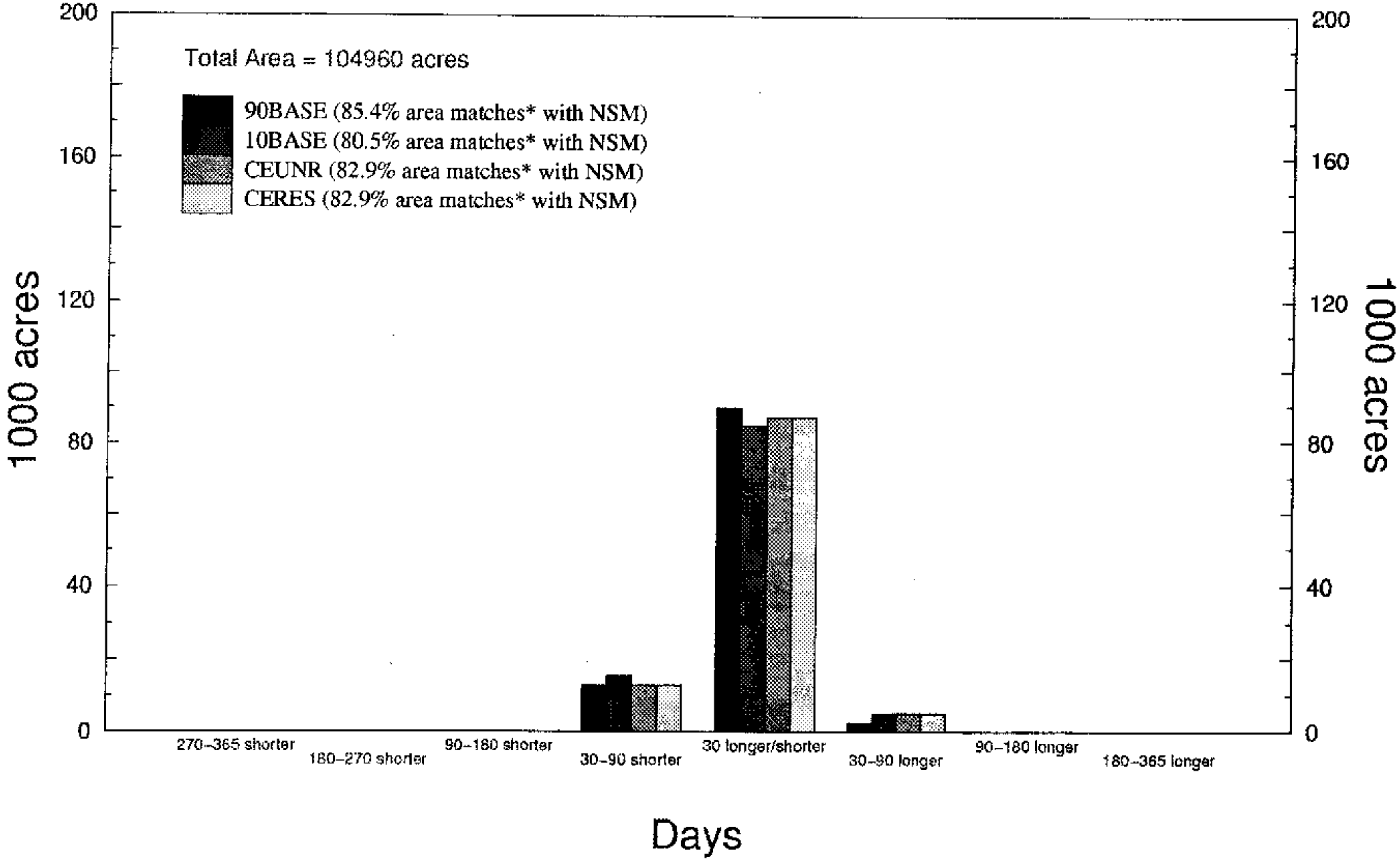


Mean NSM hydroperiod matches for WCA-1 for the 31 yr. simulation



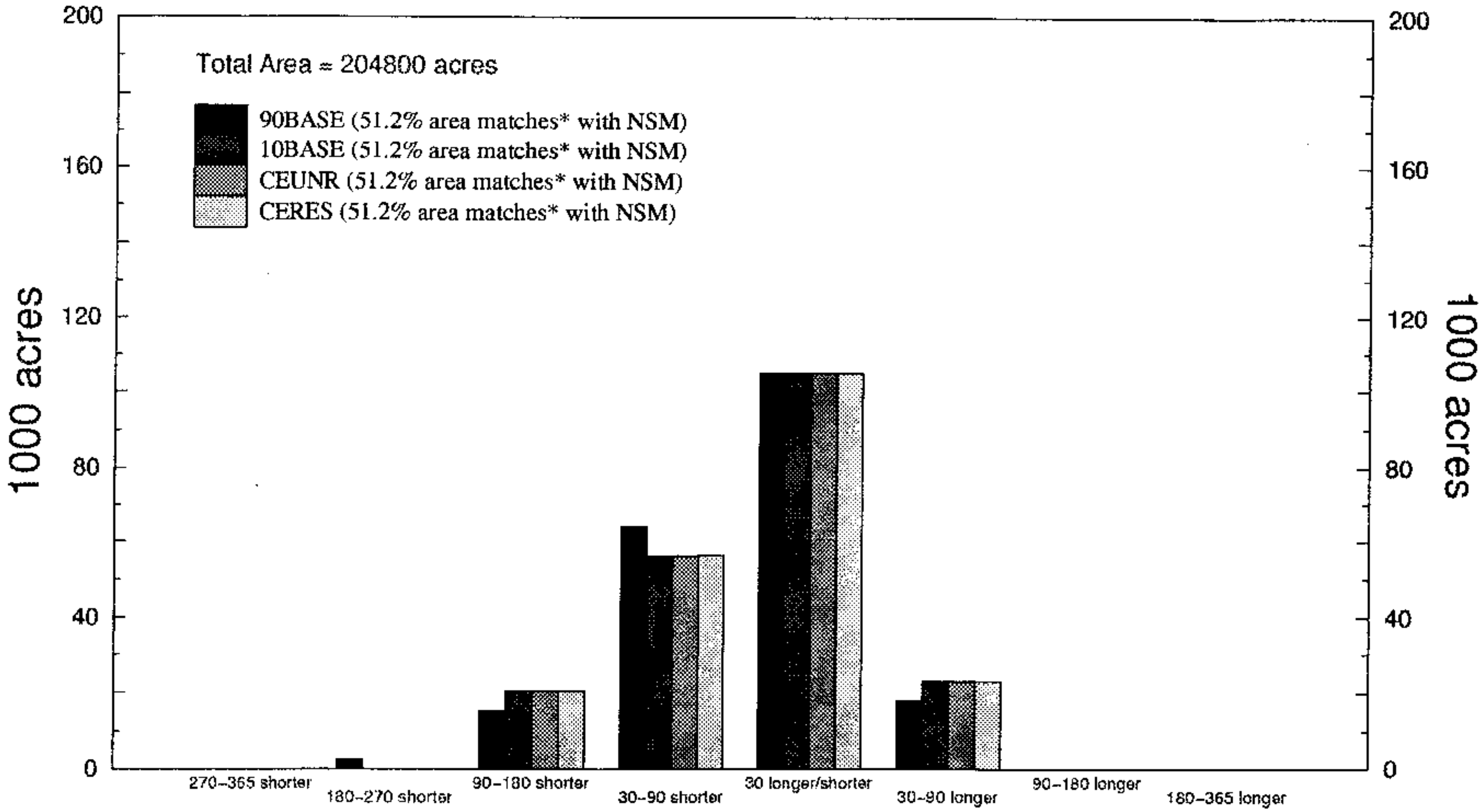
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Mean NSM hydroperiod matches for WCA-2A for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM 4.3

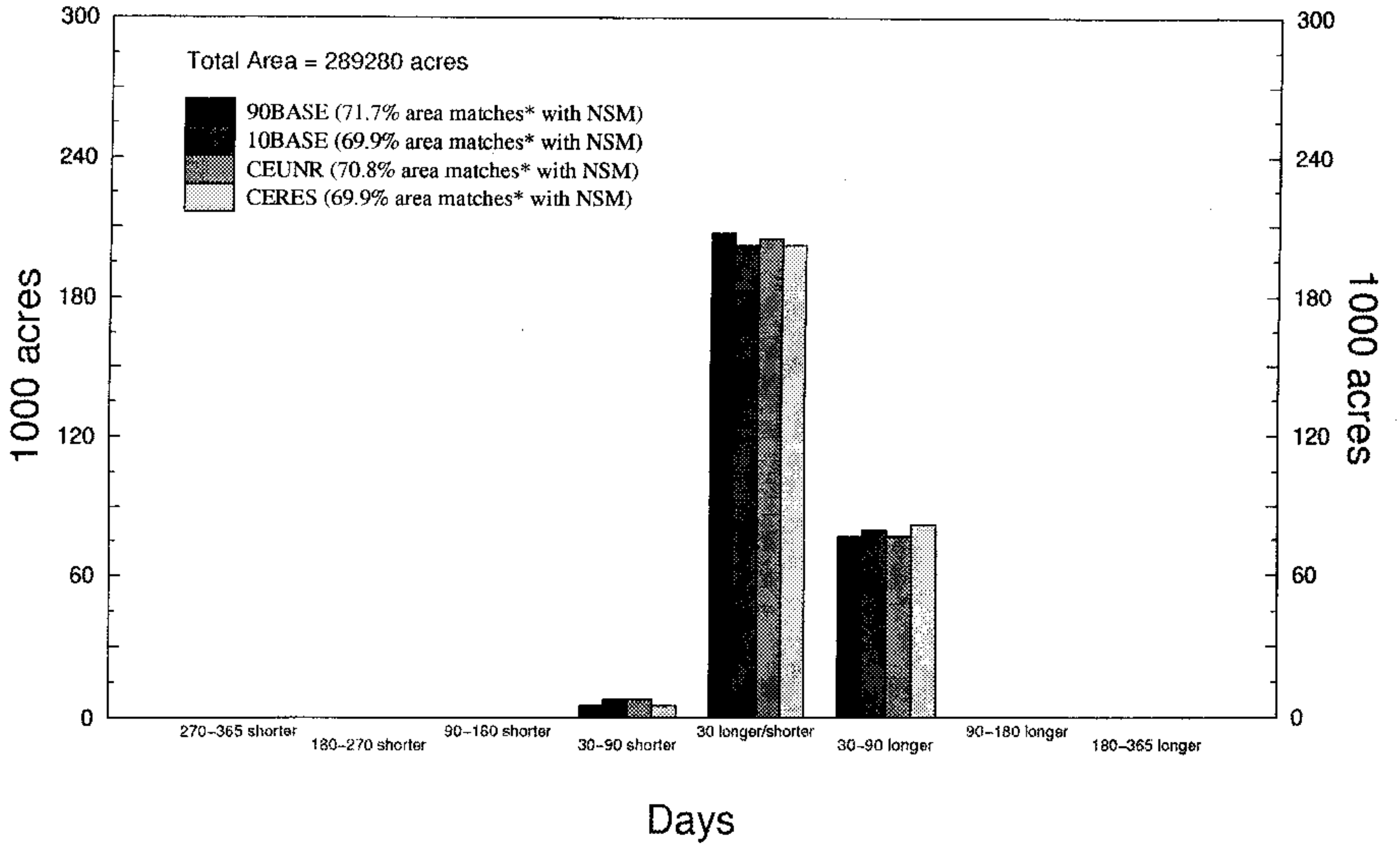
Mean NSM hydroperiod matches for WCA-3A(North) for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

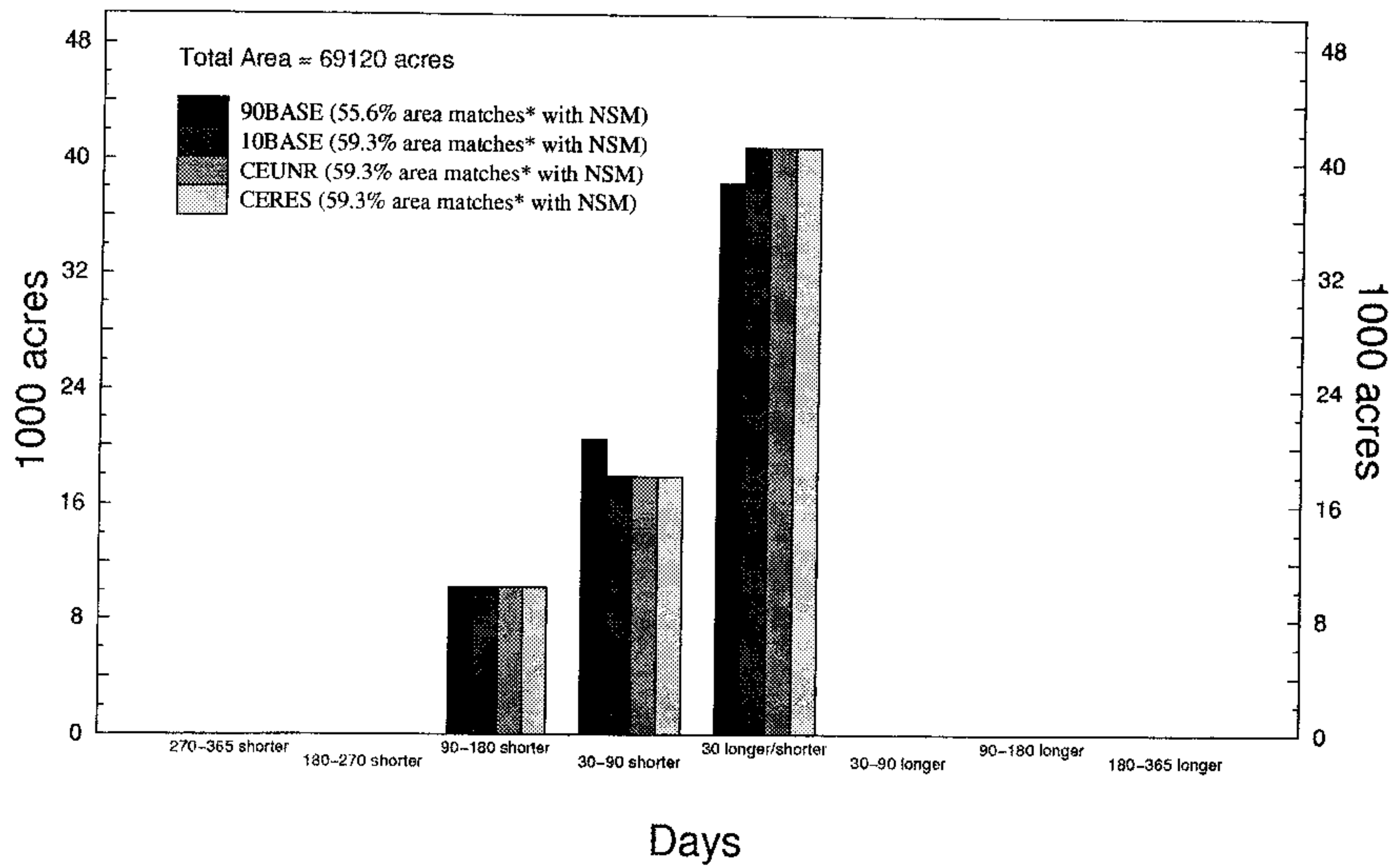
B-14

Mean NSM hydroperiod matches for WCA–3A(South) for the 31 yr. simulation

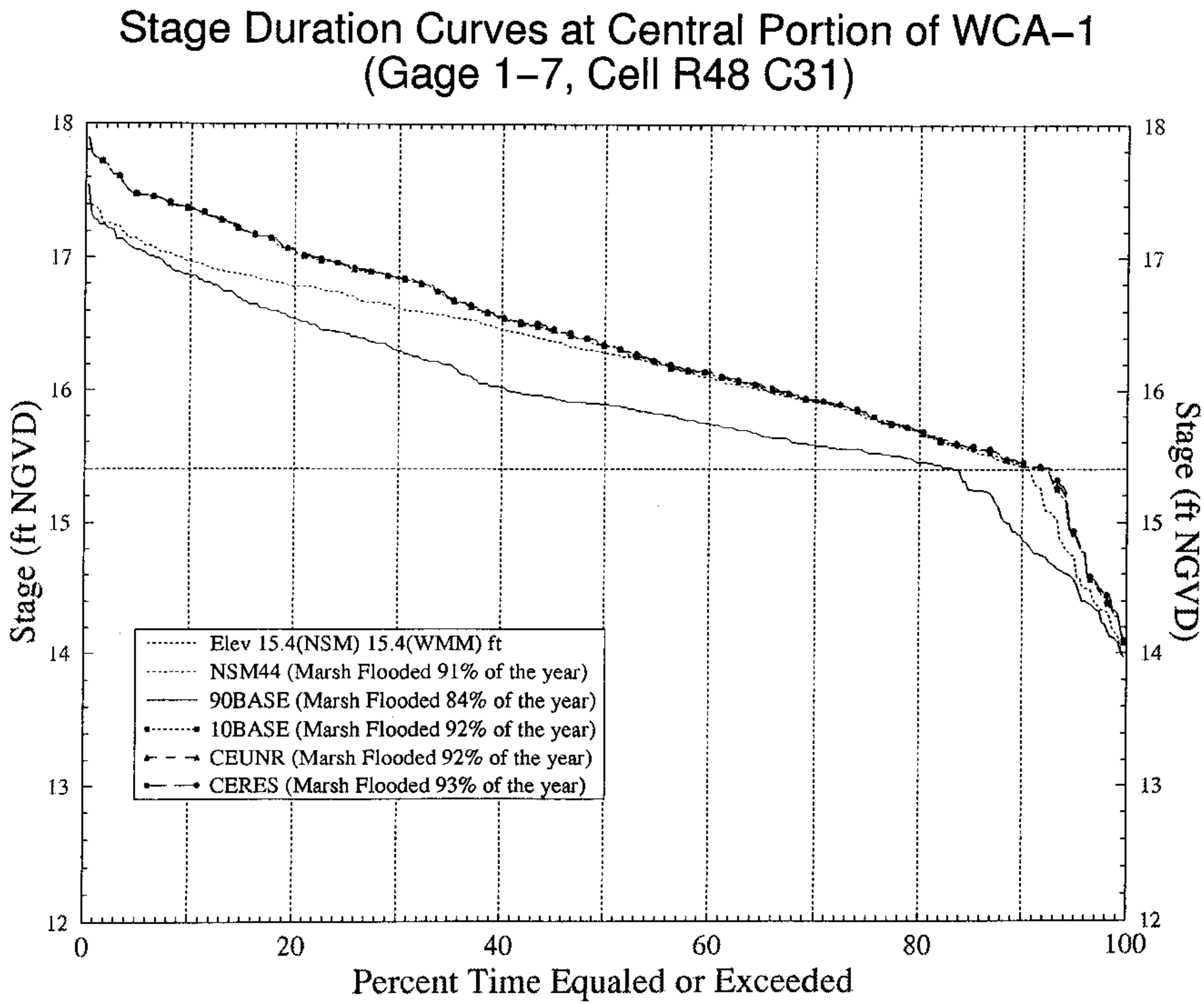


Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3

Mean NSM hydroperiod matches for WCA–3B for the 31 yr. simulation

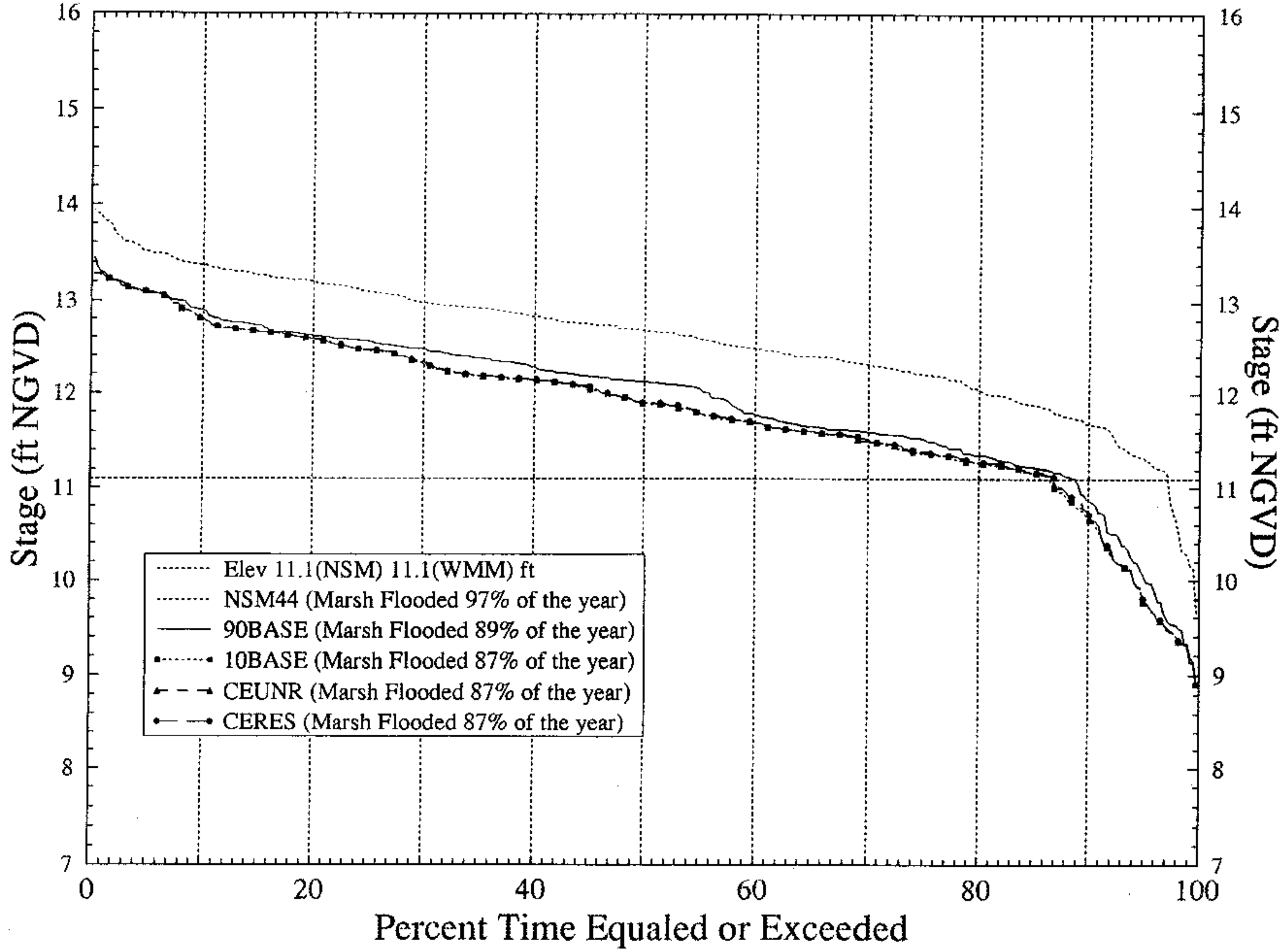


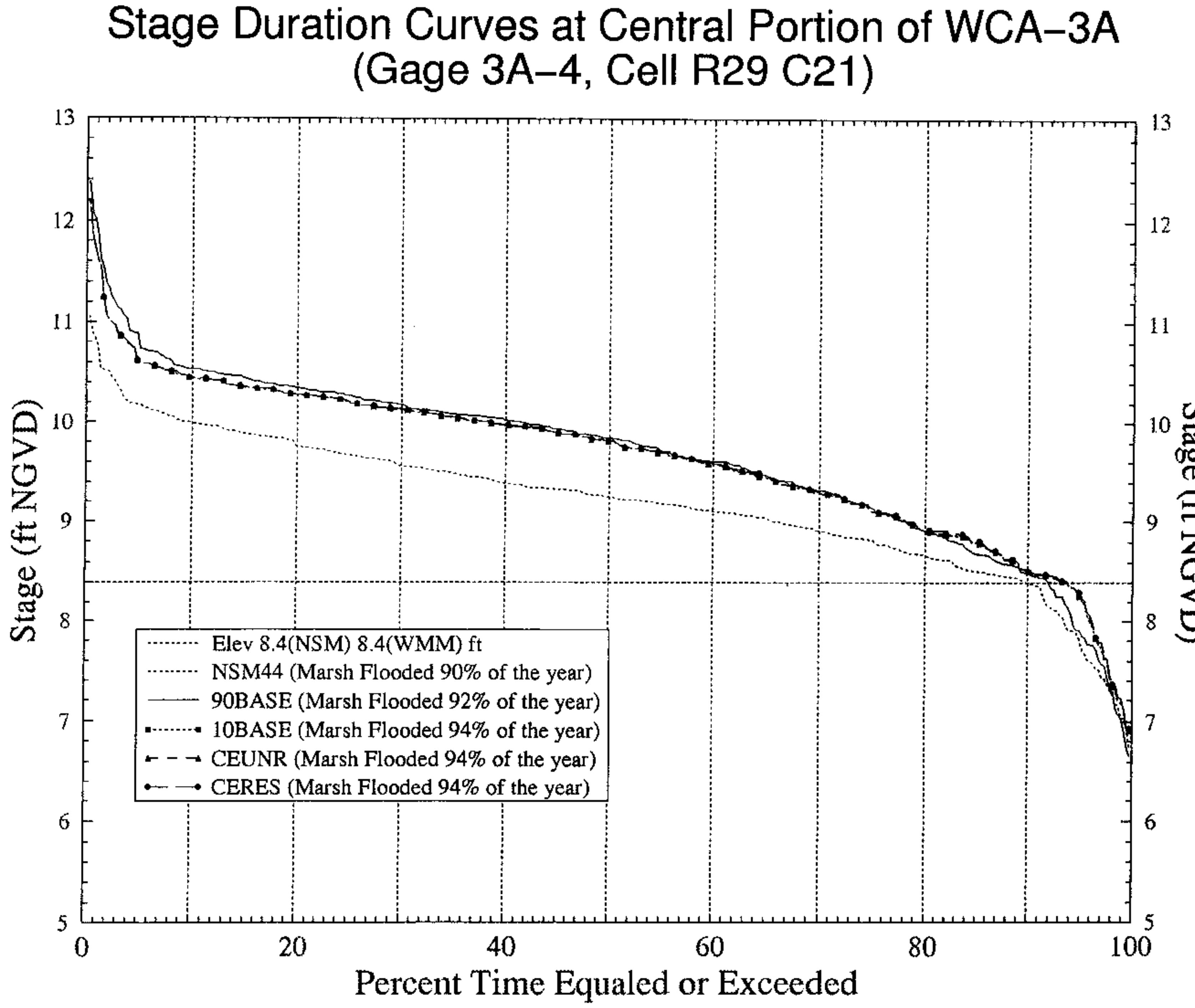
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.



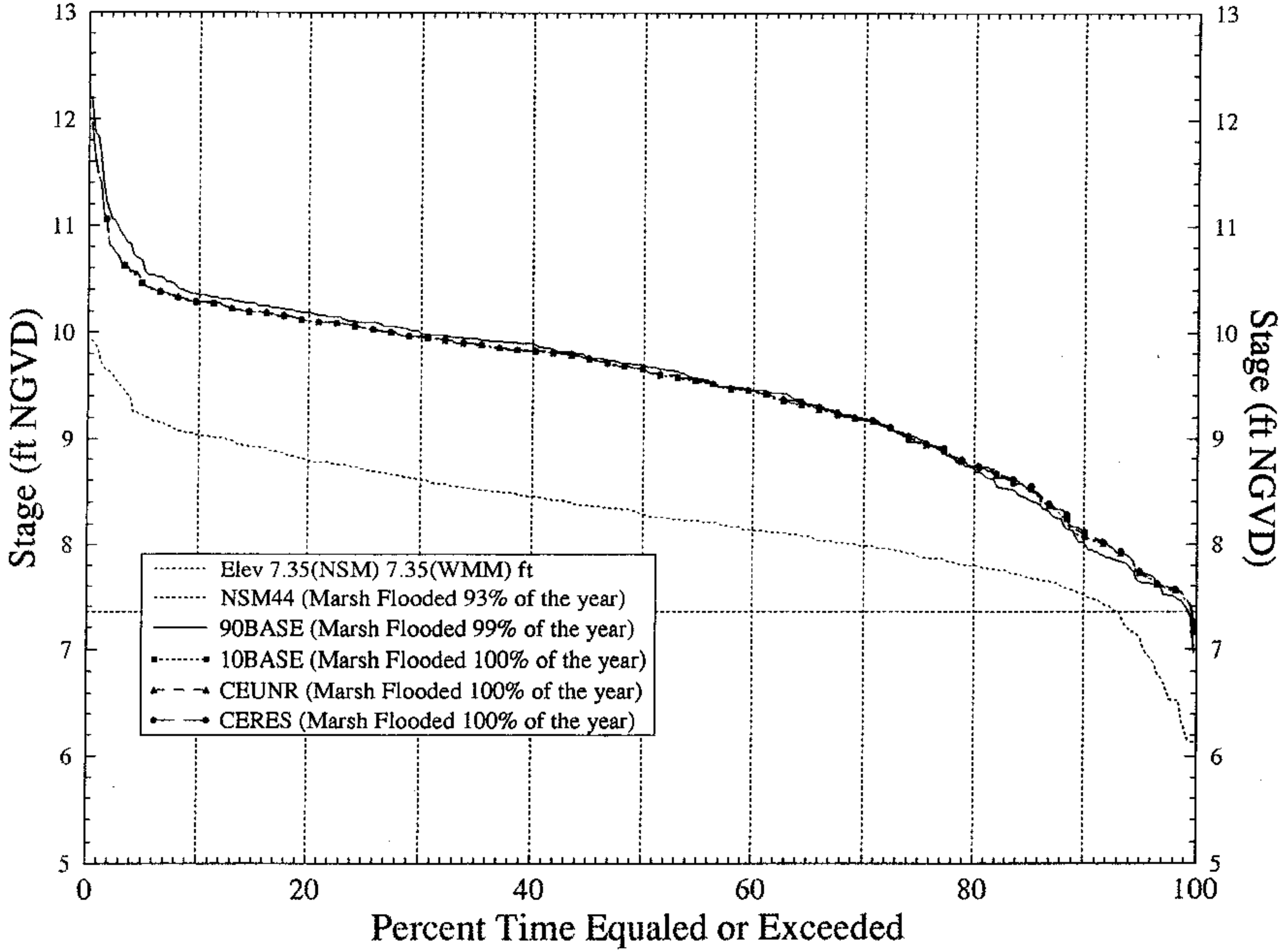
Stage Duration Curves at Central Portion of WCA-1
(Gage 1-7, Cell R48 C31)
Stage (ft NGVD)
Percent Time Equaled or Exceeded
18
17
16
15
14
13
12
0
20
40
60
80
100
Elev 15.4(NSM) 15.4(WMM) ft
NSM44 (Marsh Flooded 91% of the year)
90BASE (Marsh Flooded 84% of the year)
10BASE (Marsh Flooded 92% of the year)
CEUNR (Marsh Flooded 92% of the year)
CERES (Marsh Flooded 93% of the year)

Stage Duration Curves at Central Portion of WCA–2A (Gage 2–17, Cell R40 C29)



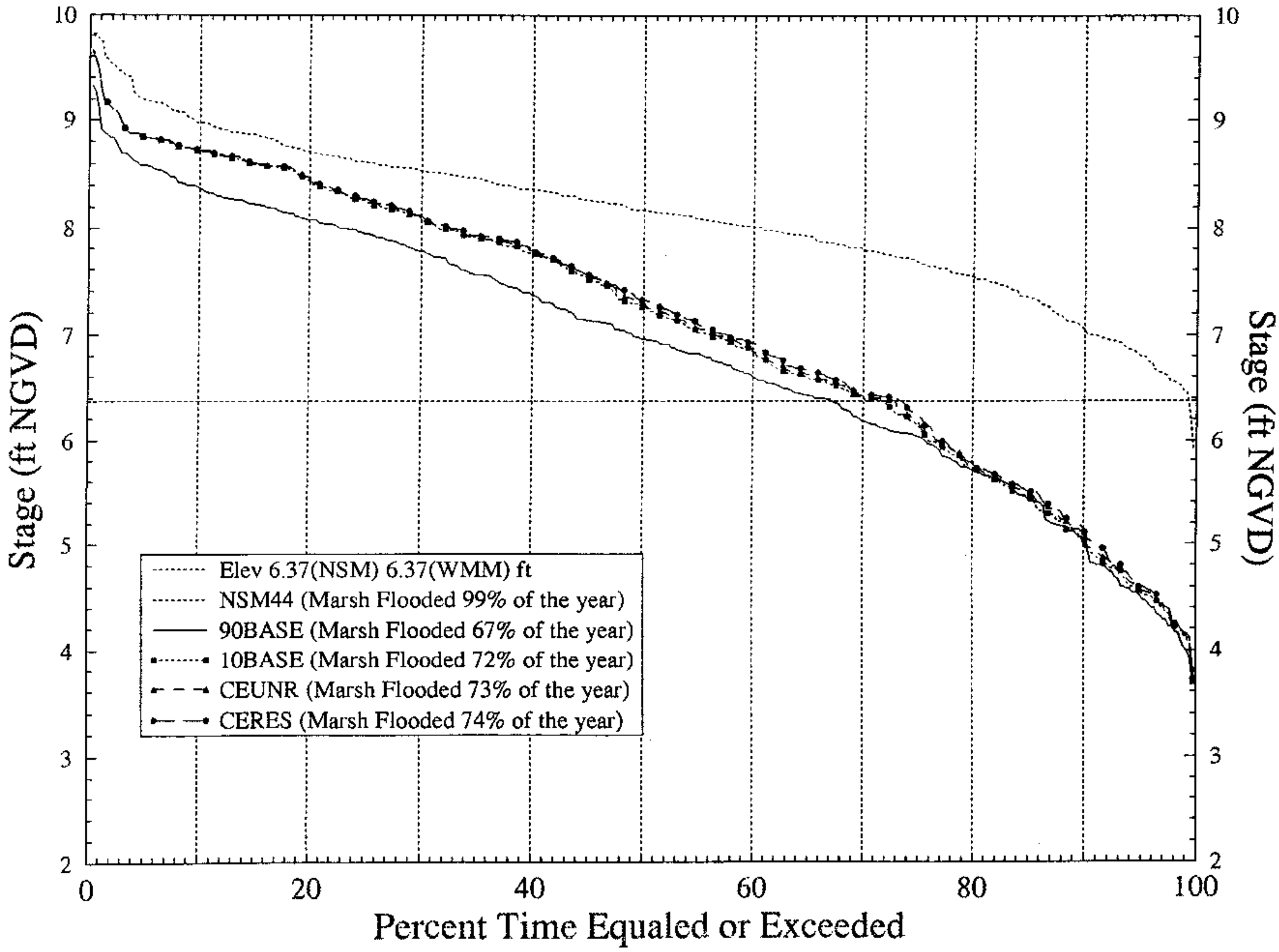

Stage Duration Curves at Central Portion of WCA−3A
(Gage 3A−4, Cell R29 C21)
Stage (ft NGVD)
Stage (ft NGVD)
Percent Time Equaled or Exceeded
Elev 8.4(NSM) 8.4(WMM) ft
NSM44 (Marsh Flooded 90% of the year)
90BASE (Marsh Flooded 92% of the year)
10BASE (Marsh Flooded 94% of the year)
CEUNR (Marsh Flooded 94% of the year)
CERES (Marsh Flooded 94% of the year)
0
20
40
60
80
100
5
6
7
8
9
10
11
12
13

Stage Duration Curves at South End of WCA-3A
(Gage 3A-28, Cell R24 C19)

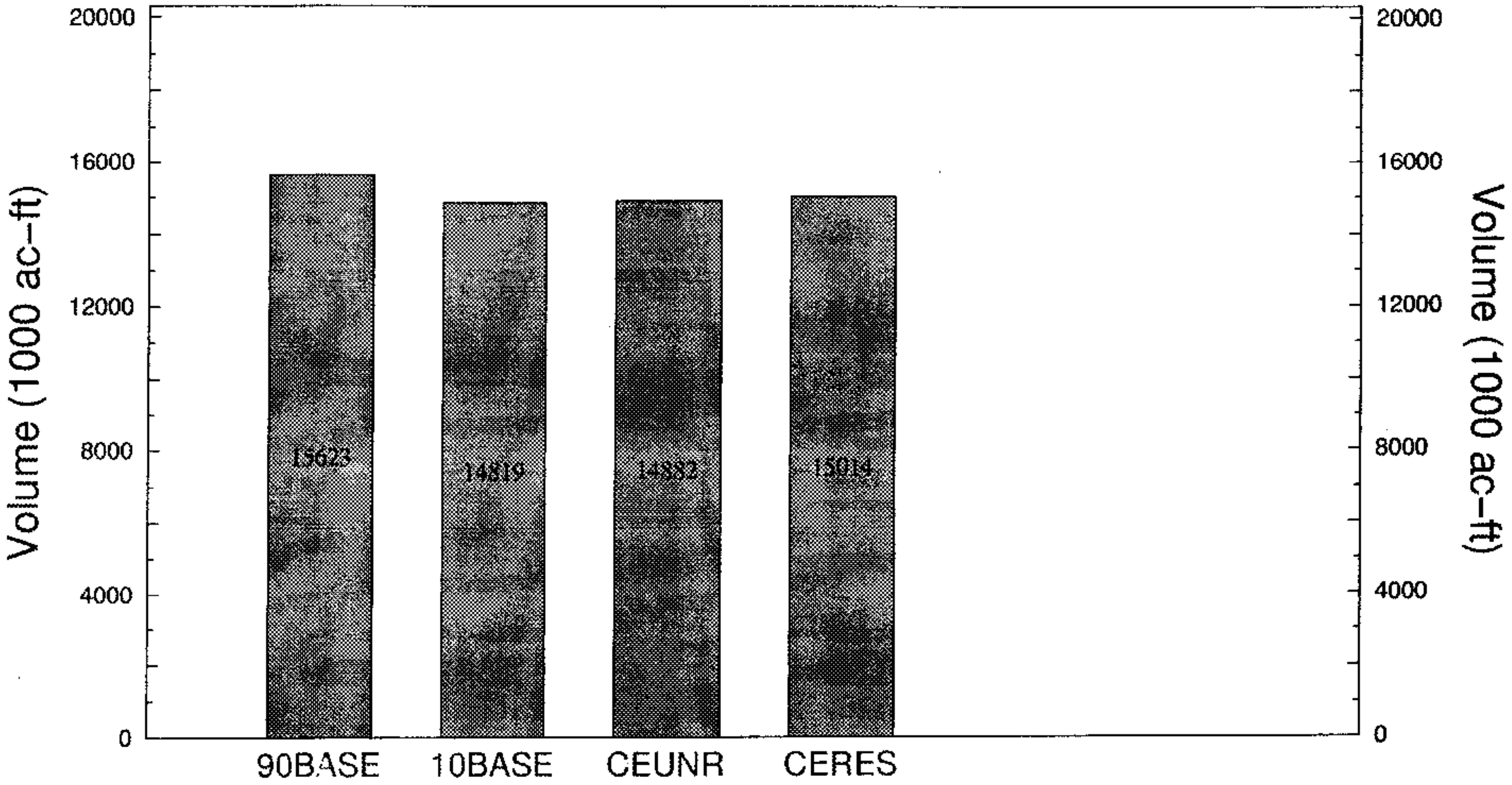


02-β

Stage Duration Curves at South End of WCA–3B
(Gage 3B–SE, Cell R23 C26)

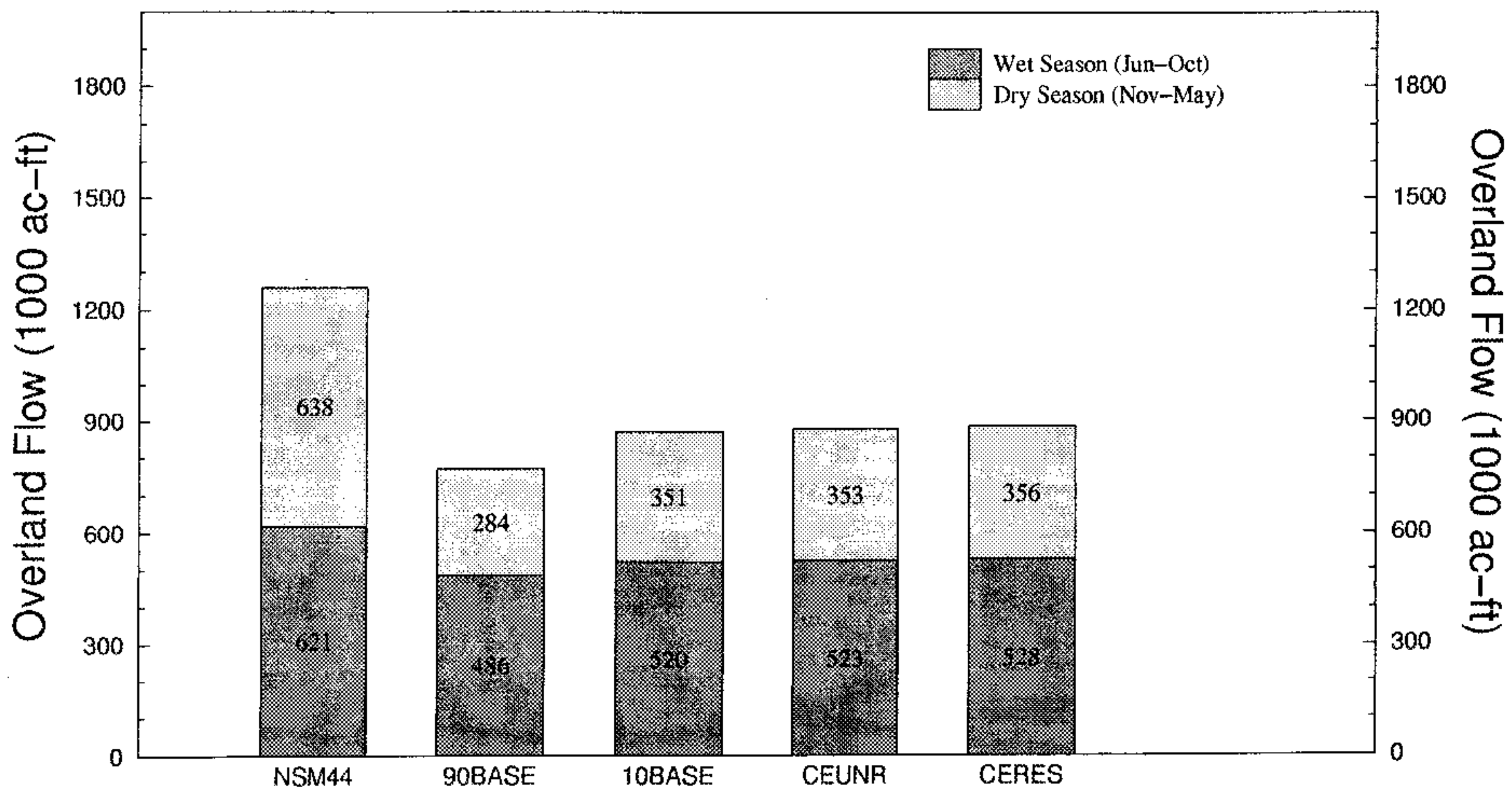


Total Flood Control Releases from WCA–3 to ENP for the 31 yr simulation period



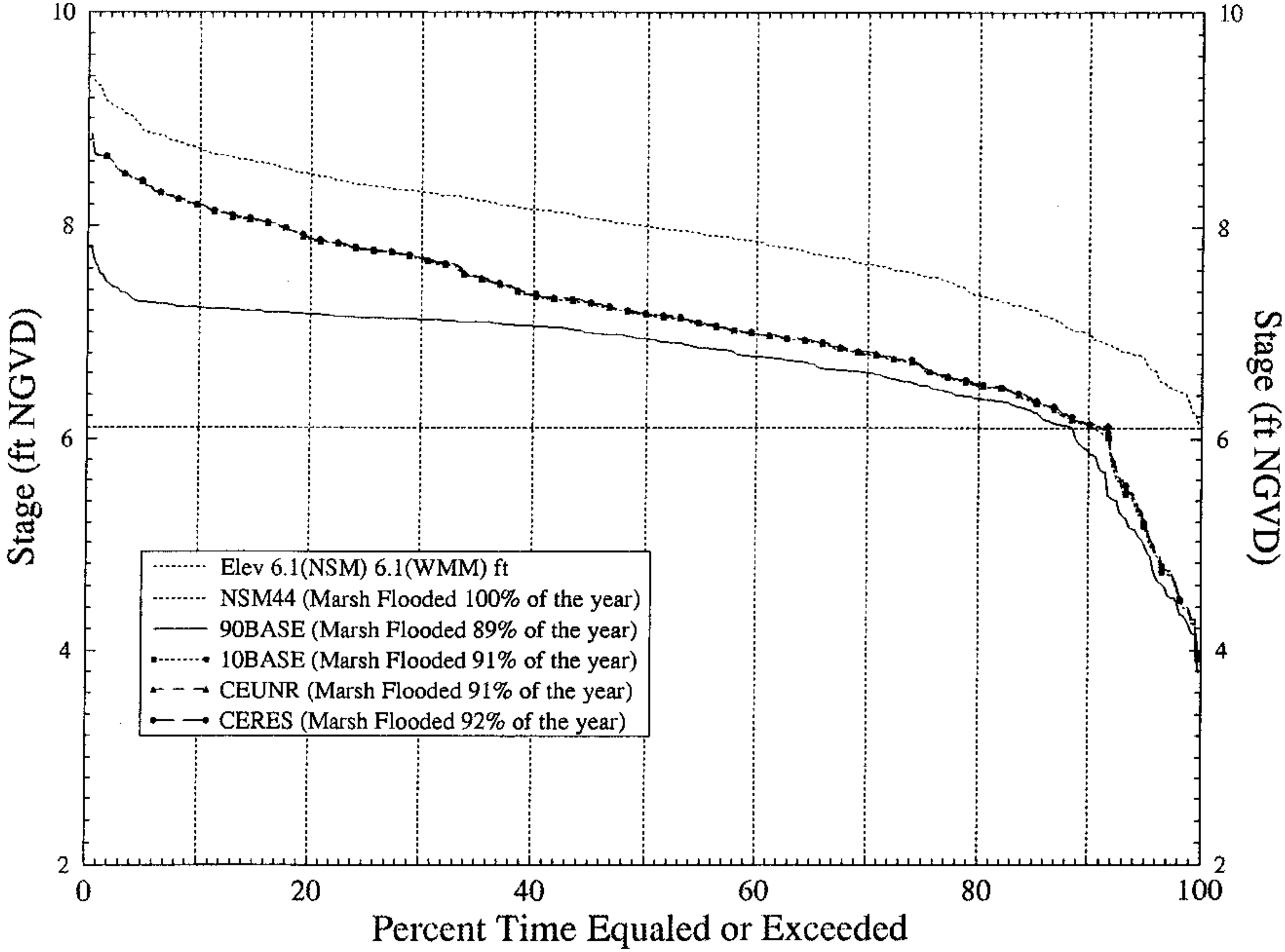
Note: Flow represents total of S12REG + S333REG + S355REG.

Wet/Dry Season Average Overland Flows South of Tamiami Trail to ENP for the 31 yr. simulation

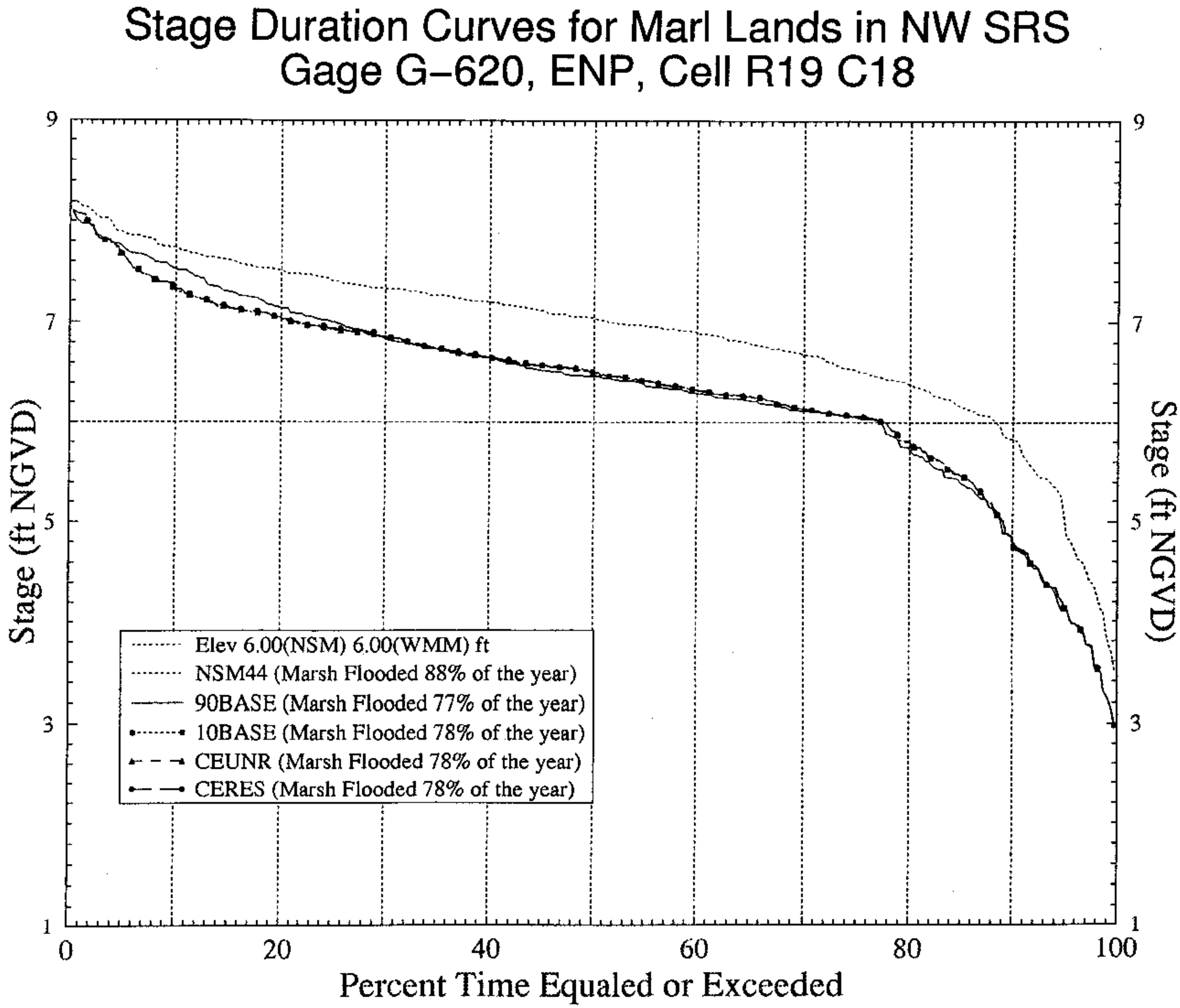


Note: Flow represents overland flows for cells Row 22 Columns 17 thru 26. NSM water depths at key ENP gage locations are used as operational

Stage Duration Curves at N.E. Shark River Slough
Gage NESRS–2, Cell R21 C24



B-24

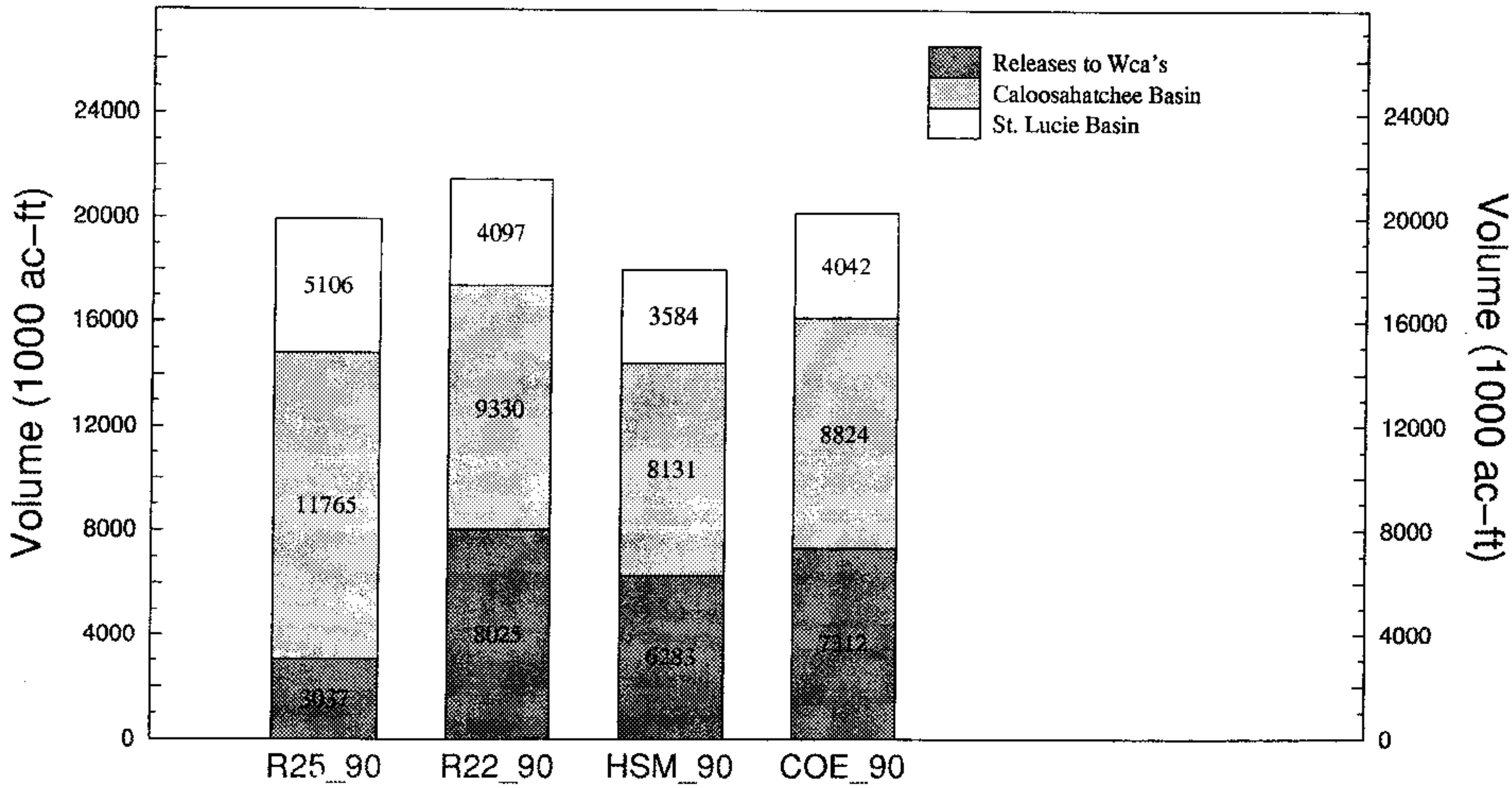


Stage Duration Curves for Marl Lands in NW SRS
Gage G–620, ENP, Cell R19 C18
Stage (ft NGVD)
Stage (ft NGVD)
Percent Time Equaled or Exceeded
9
7
5
3
1
0
20
40
60
80
100
Elev 6.00(NSM) 6.00(WMM) ft
NSM44 (Marsh Flooded 88% of the year)
90BASE (Marsh Flooded 77% of the year)
10BASE (Marsh Flooded 78% of the year)
CEUNR (Marsh Flooded 78% of the year)
CERES (Marsh Flooded 78% of the year)

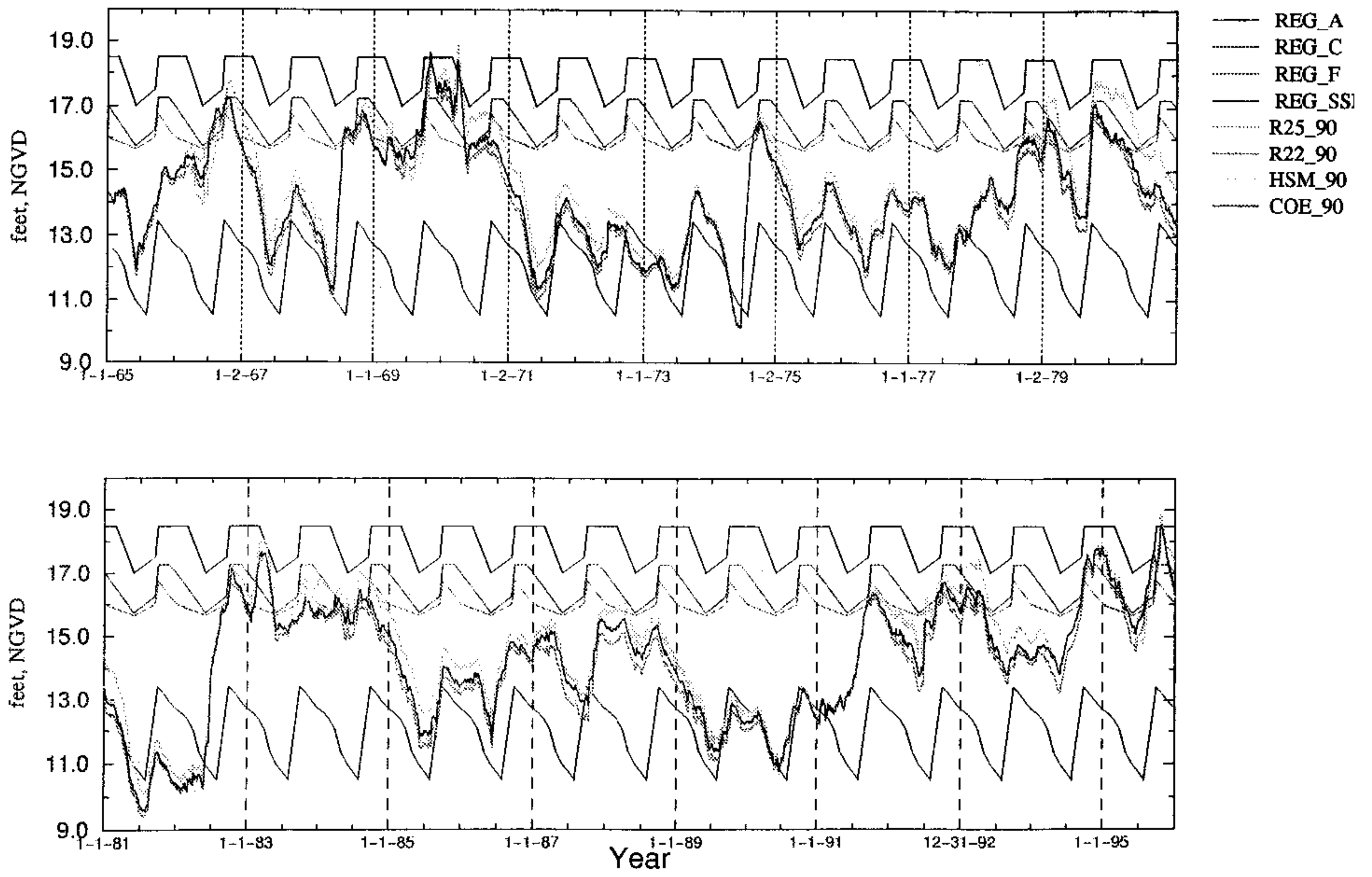
APPENDIX C. 1990 Simulations - Performance Measure Graphics

Performance Measures for
Lake Okeechobee

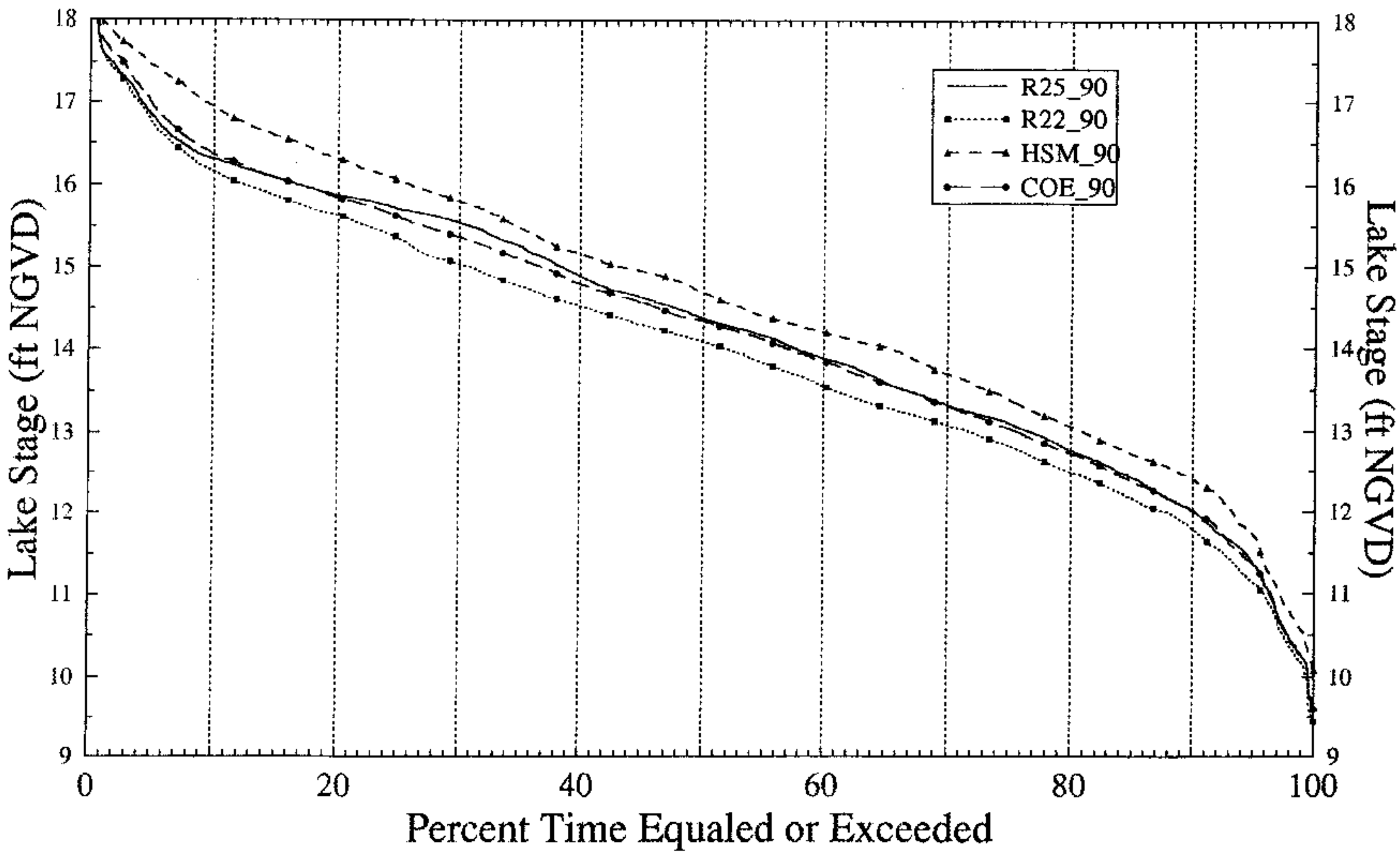
Total Flood Control Releases from Lake Okeechobee for the 31 yr (1965 – 1995) Simulation

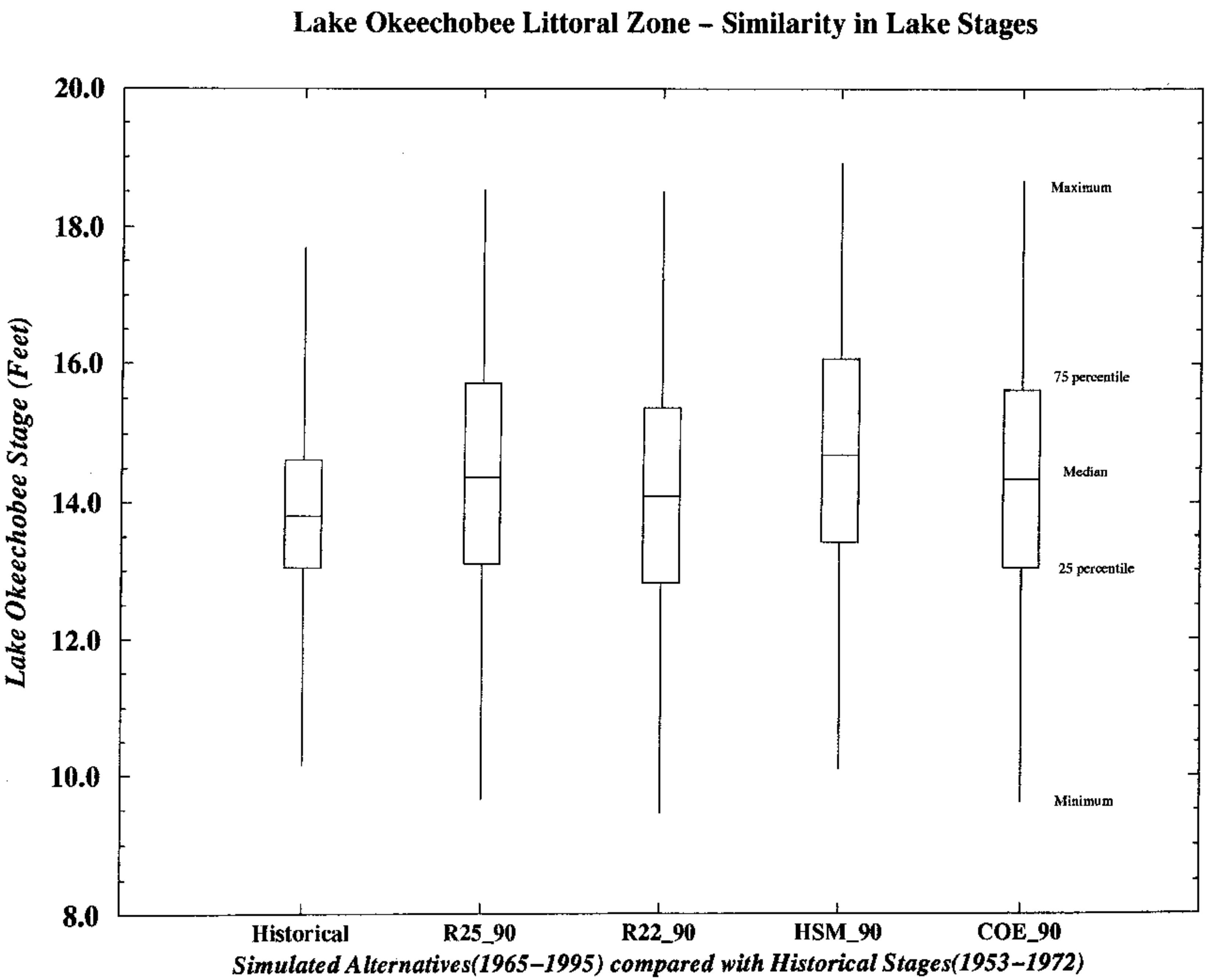


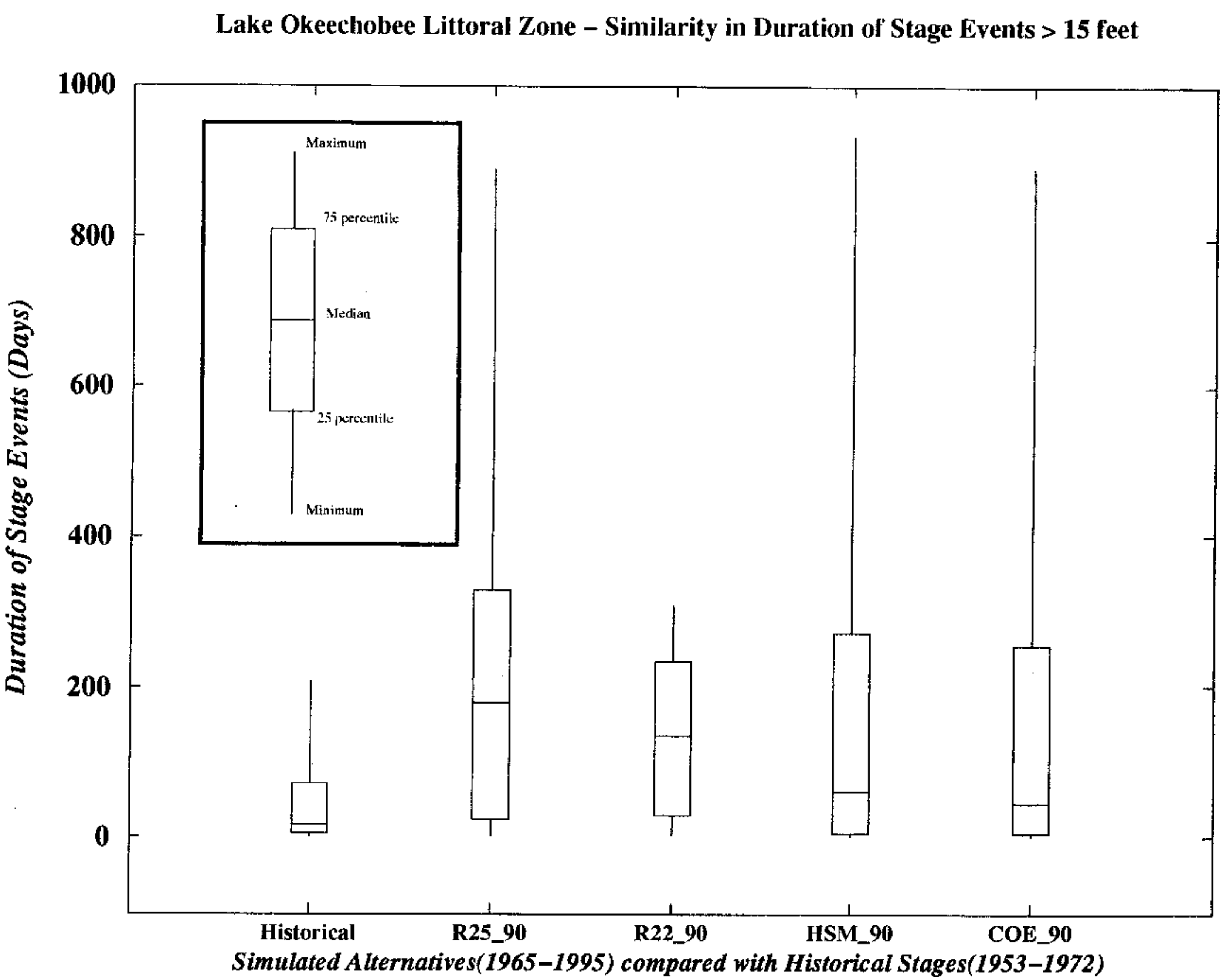
Daily Stage Hydrographs for Lake Okeechobee



Lake Okeechobee Stage Duration Curves

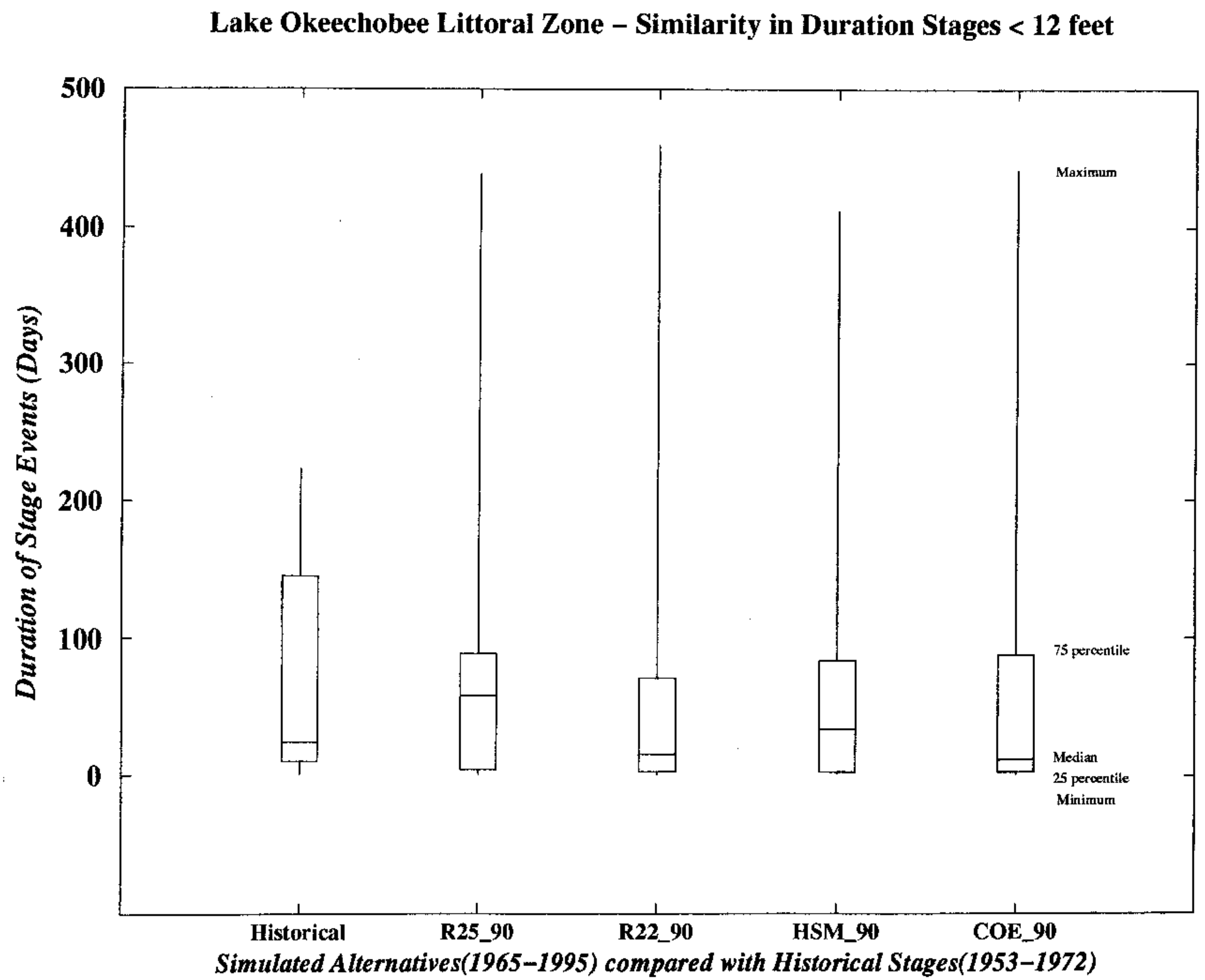



Lake Okeechobee Littoral Zone – Similarity in Lake Stages
20.0
18.0
16.0
14.0
12.0
10.0
8.0
Lake Okeechobee Stage (Feet)
Maximum
75 percentile
Median
25 percentile
Minimum
Historical
R25_90
R22_90
HSM_90
COE_90
Simulated Alternatives(1965–1995) compared with Historical Stages(1953–1972)

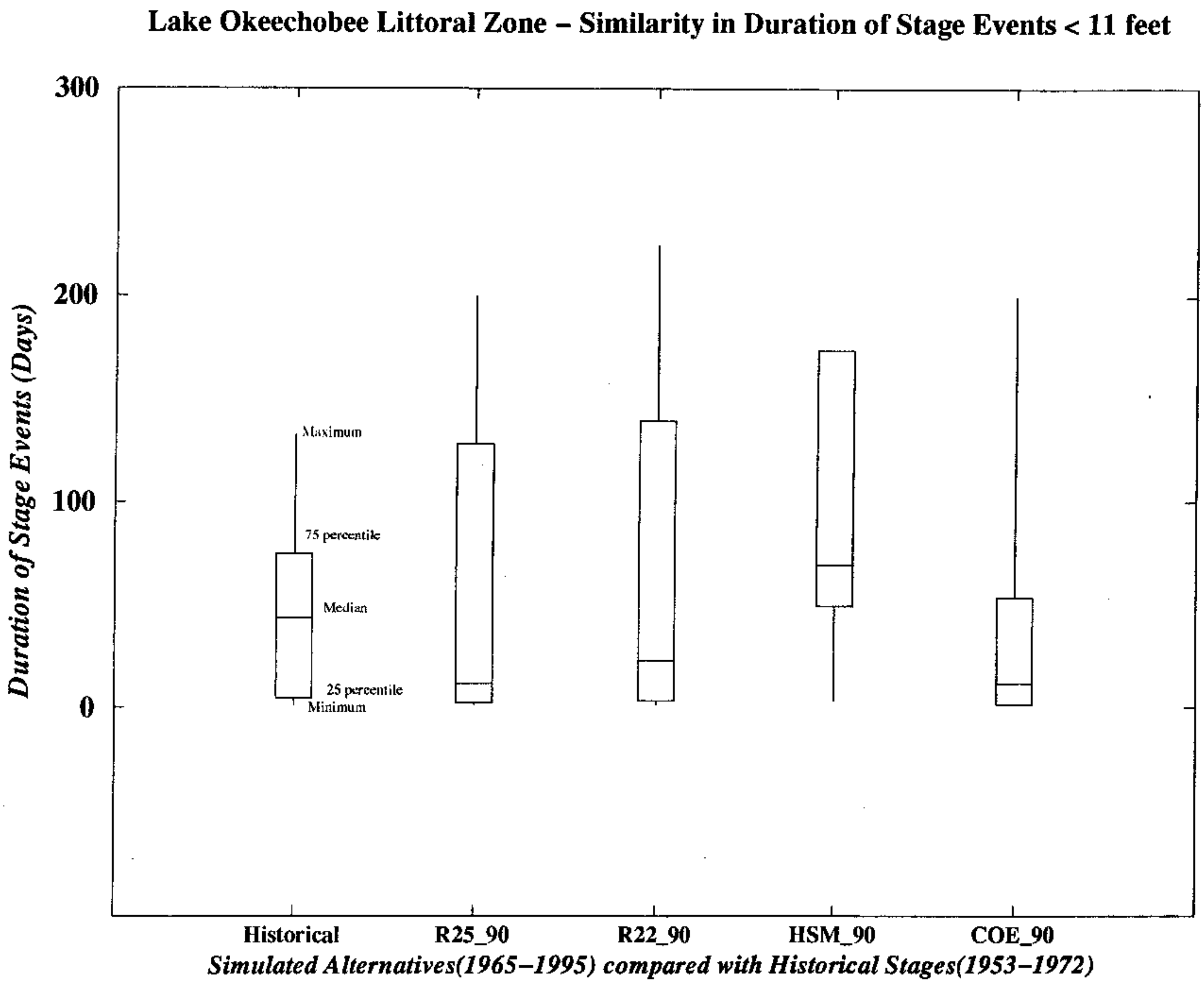


Lake Okeechobee Littoral Zone – Similarity in Duration of Stage Events > 15 feet
1000
800
600
400
200
0
Duration of Stage Events (Days)
Maximum
75 percentile
Median
25 percentile
Minimum
Historical
R25_90
R22_90
HSM_90
COE_90
Simulated Alternatives(1965–1995) compared with Historical Stages(1953–1972)

C-6

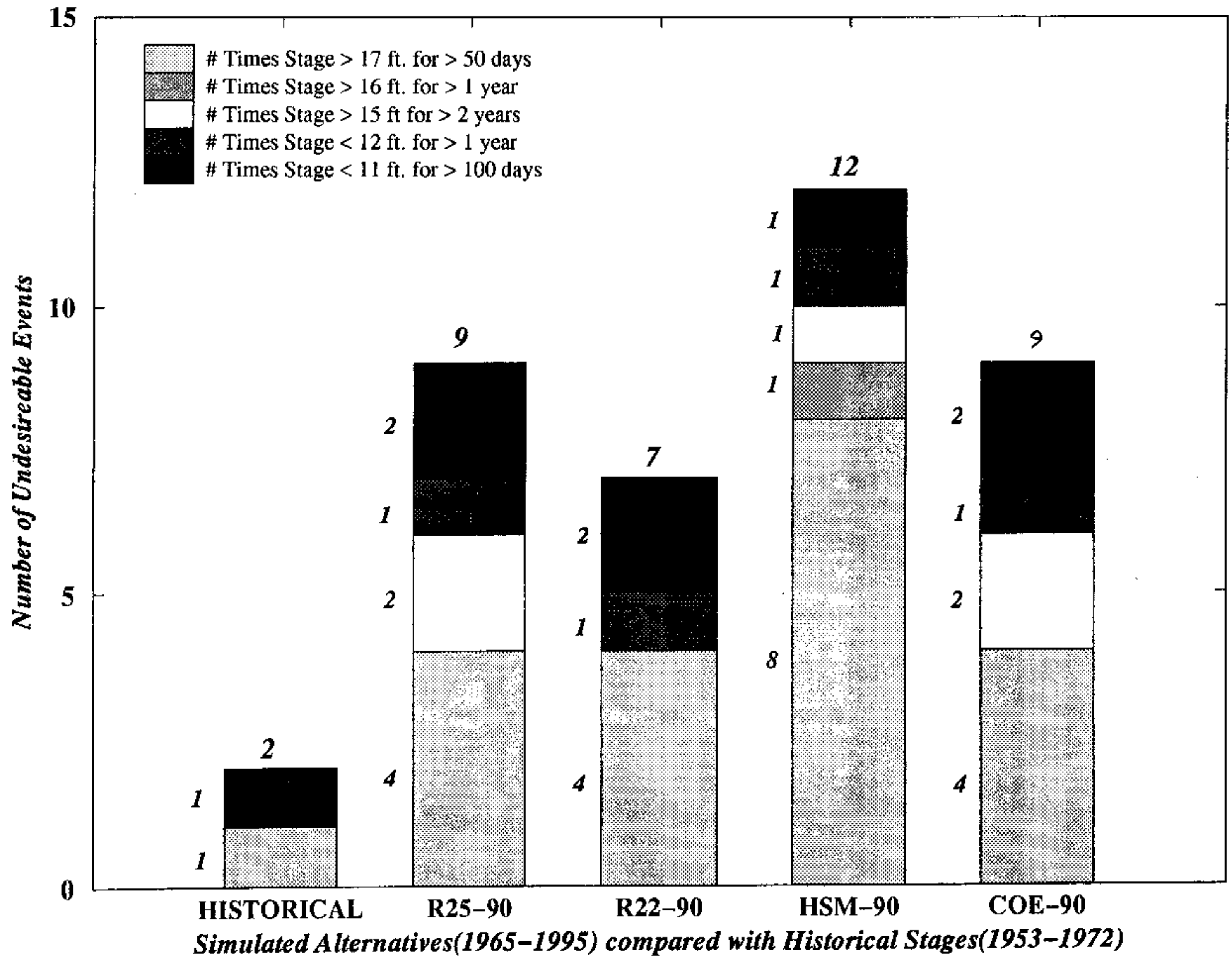

Lake Okeechobee Littoral Zone – Similarity in Duration Stages < 12 feet
Duration of Stage Events (Days)
500
400
300
200
100
0
Maximum
75 percentile
Median
25 percentile
Minimum
Historical
R25_90
R22_90
HSM_90
COE_90
Simulated Alternatives(1965–1995) compared with Historical Stages(1953–1972)

L-3



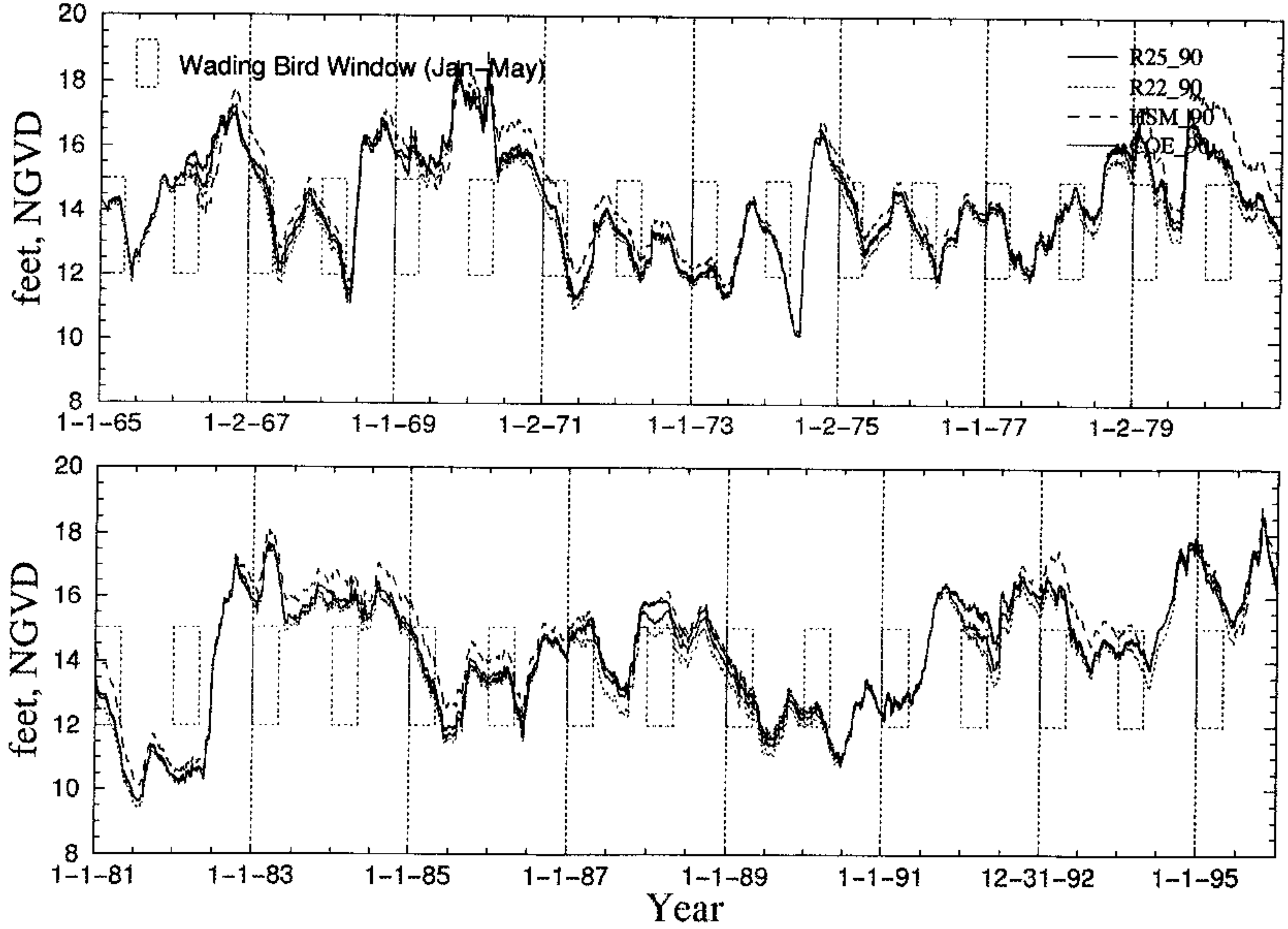
Lake Okeechobee Littoral Zone – Similarity in Duration of Stage Events < 11 feet
300
200
100
0
Duration of Stage Events (Days)
Maximum
75 percentile
Median
25 percentile
Minimum
Historical
R25_90
R22_90
HSM_90
COE_90
Simulated Alternatives(1965–1995) compared with Historical Stages(1953–1972)

Number of Undesireable Lake Okeechobee Stage Events



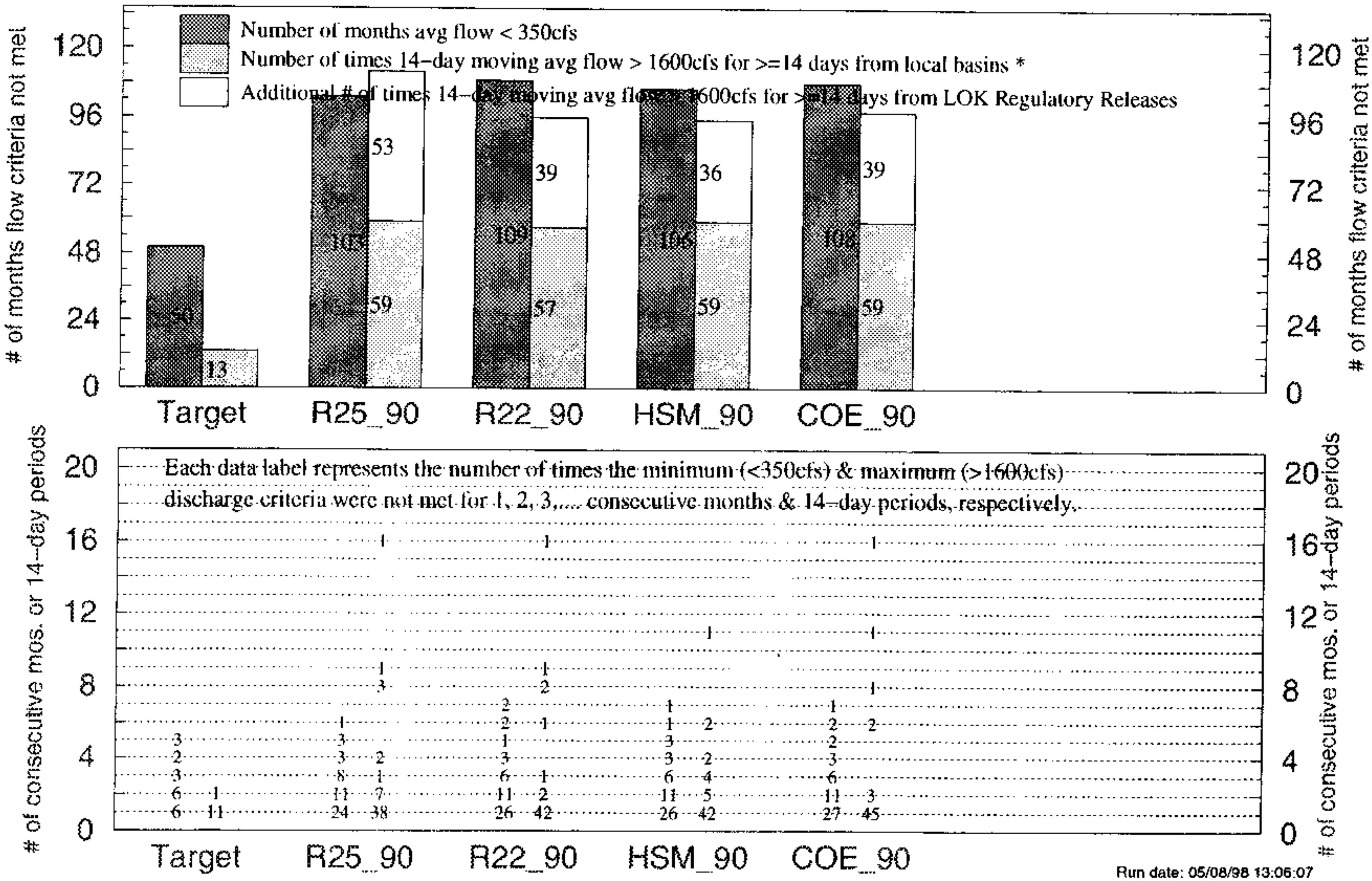
C-9

Daily Stage Hydrographs for Lake Okeechobee Wading Bird Windows



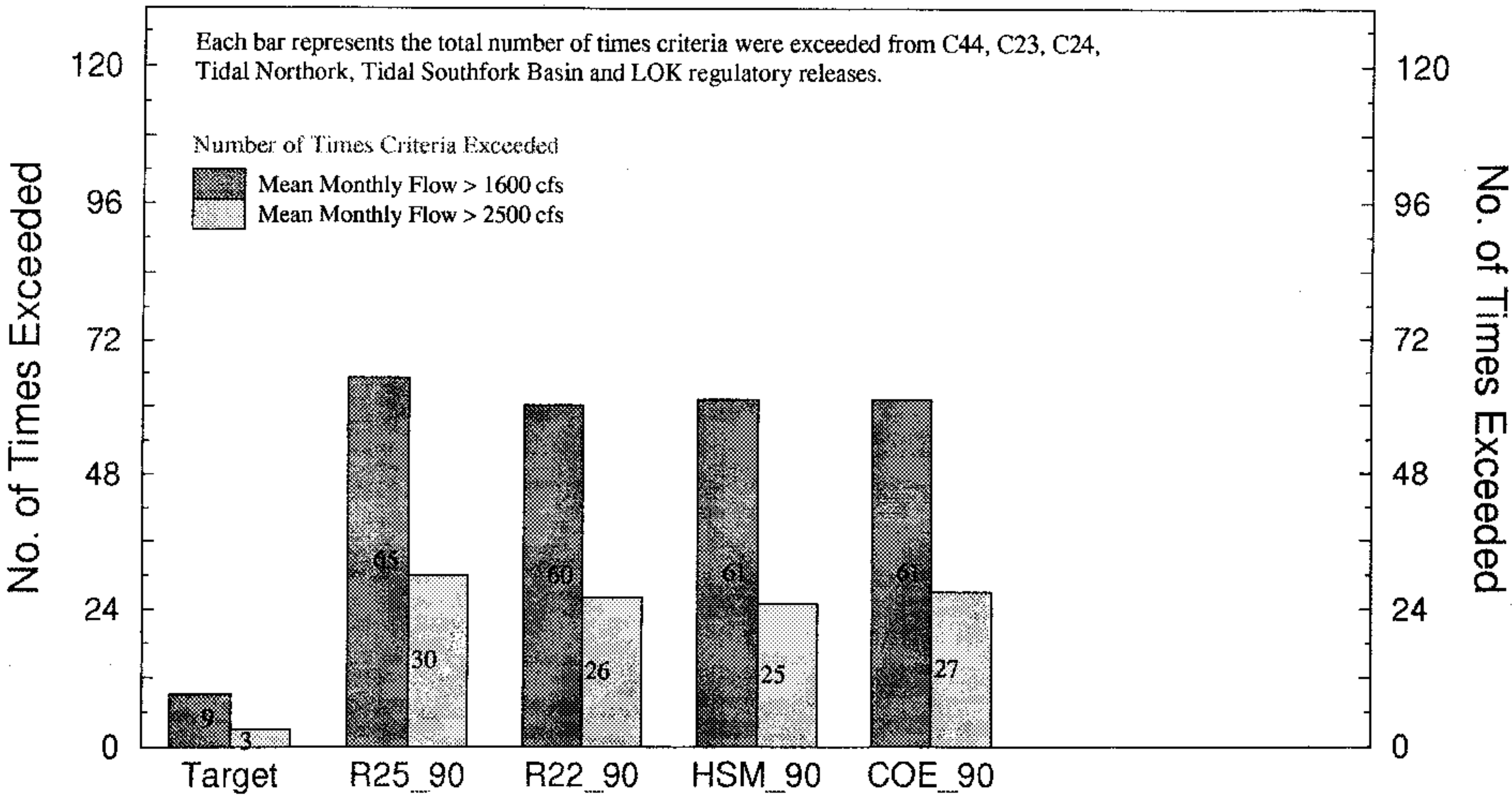
Performance Measures for the
Caloosahatchee and St. Lucie Estuaries

Number of times Salinity Envelope Criteria were NOT met for the St. Lucie Estuary



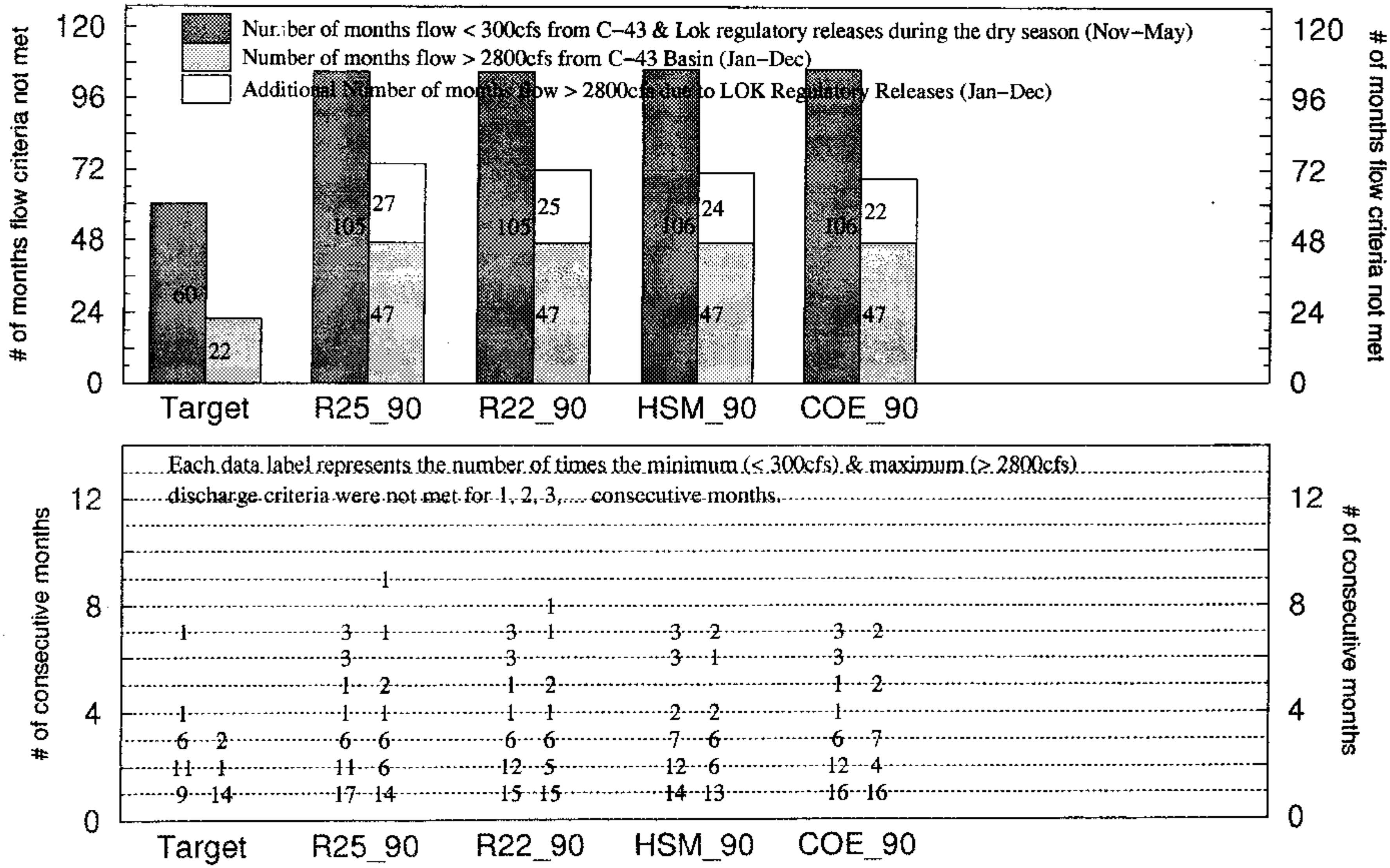
Run date: 05/08/98 13:06:07
For Planning Purposes Only
SFWMM V3.2

Number of Times High Discharge Criteria (mean monthly flows > 1600 & 2500 cfs) were exceeded for the St. Lucie Estuary

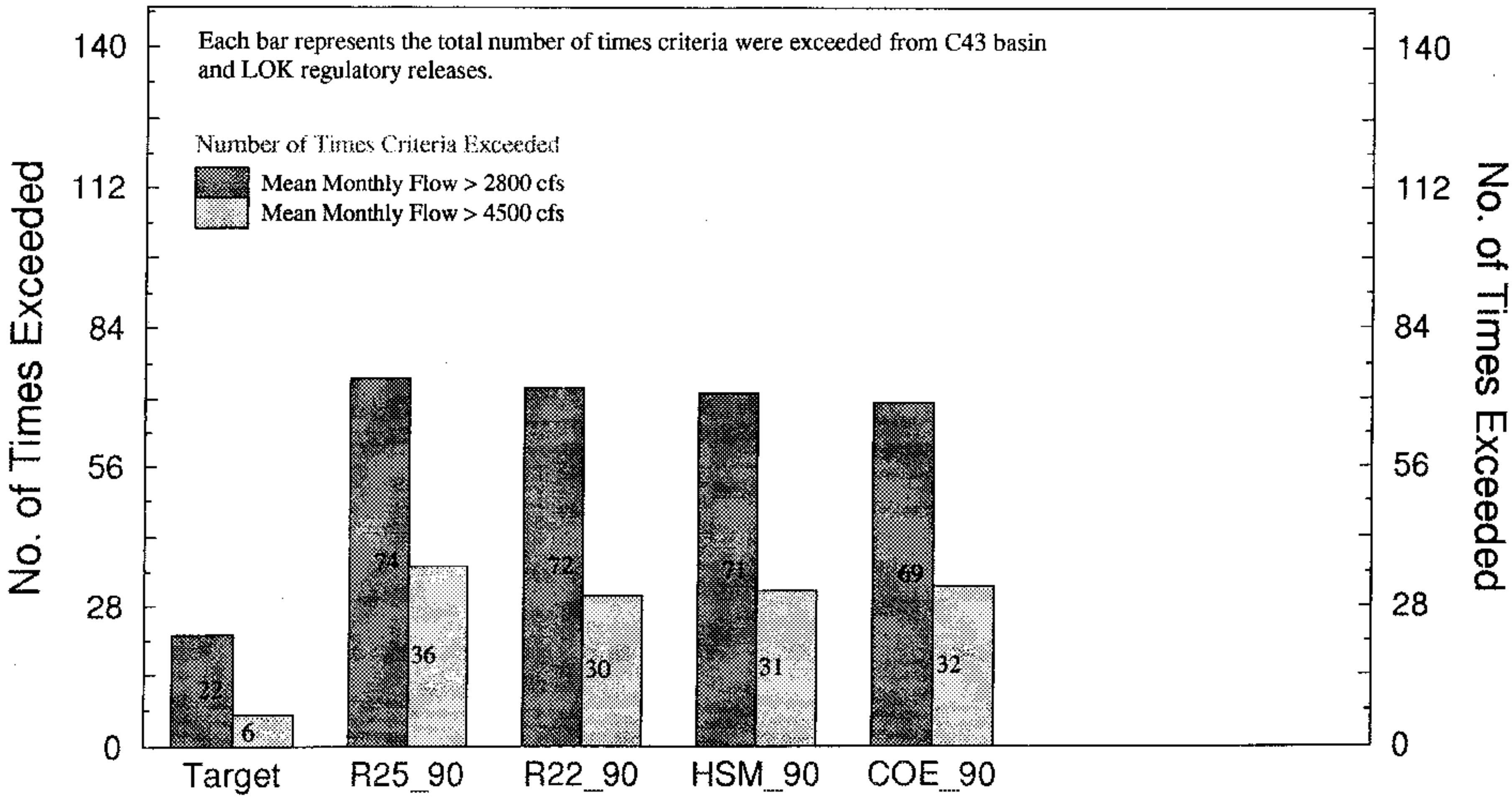


Note: A favorable maximum monthly flow was developed for the estuary (1600 cfs) that will theoretically provide suitable salinity conditions which promote the development of important benthic communities (eg. oysters & shoalgrass). Mean monthly flows above 2500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota.

Number of times Salinity Envelope Criteria were NOT met
for the Caloosahatchee Estuary (mean monthly flows 1965 – 1995)



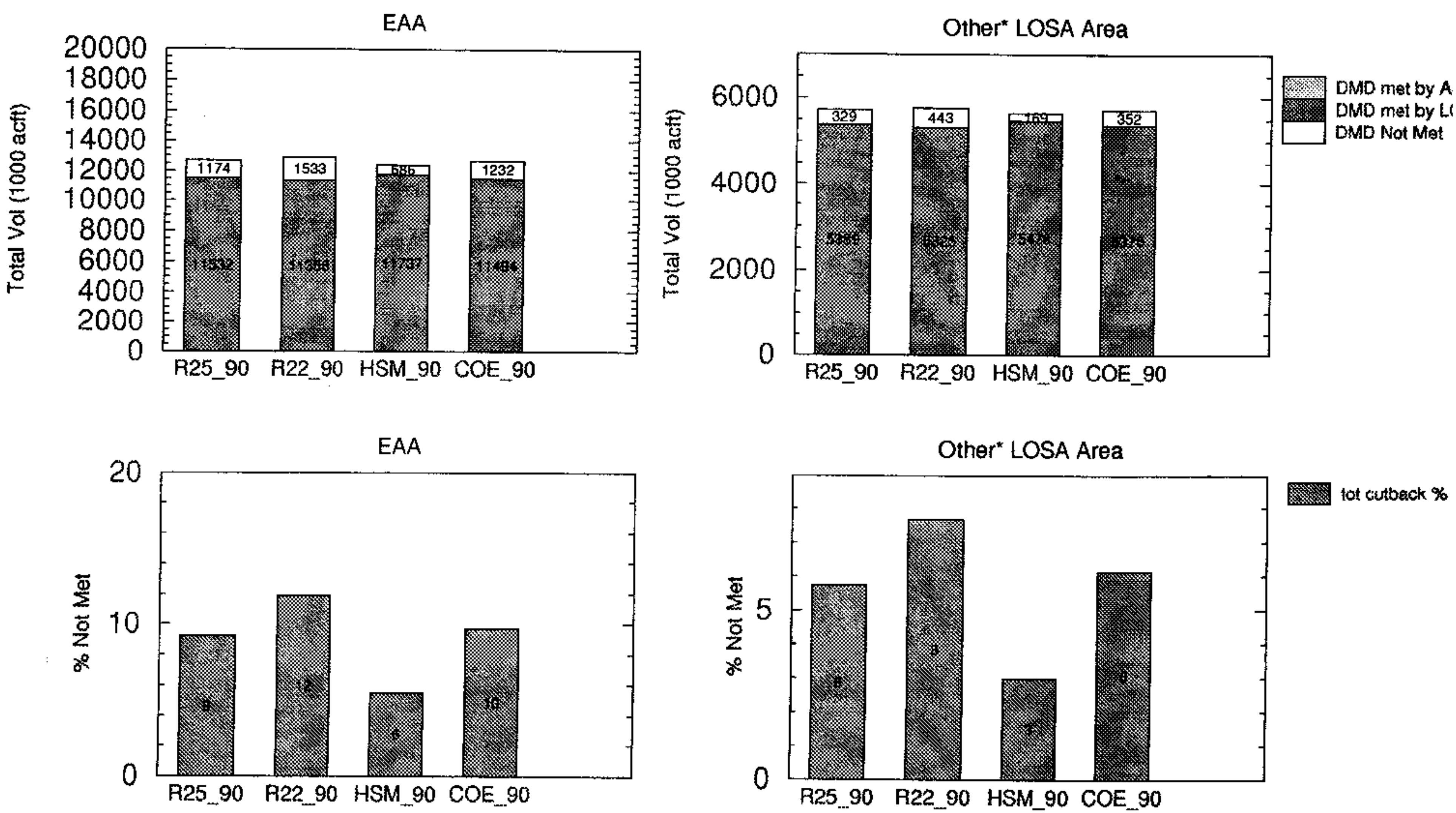
Number of Times High Discharge Criteria (mean monthly flows > 2800 & 4500 cfs) were exceeded for the Caloosahatchee Estuary



Performance Measures for the
Lake Okeechobee Service Area

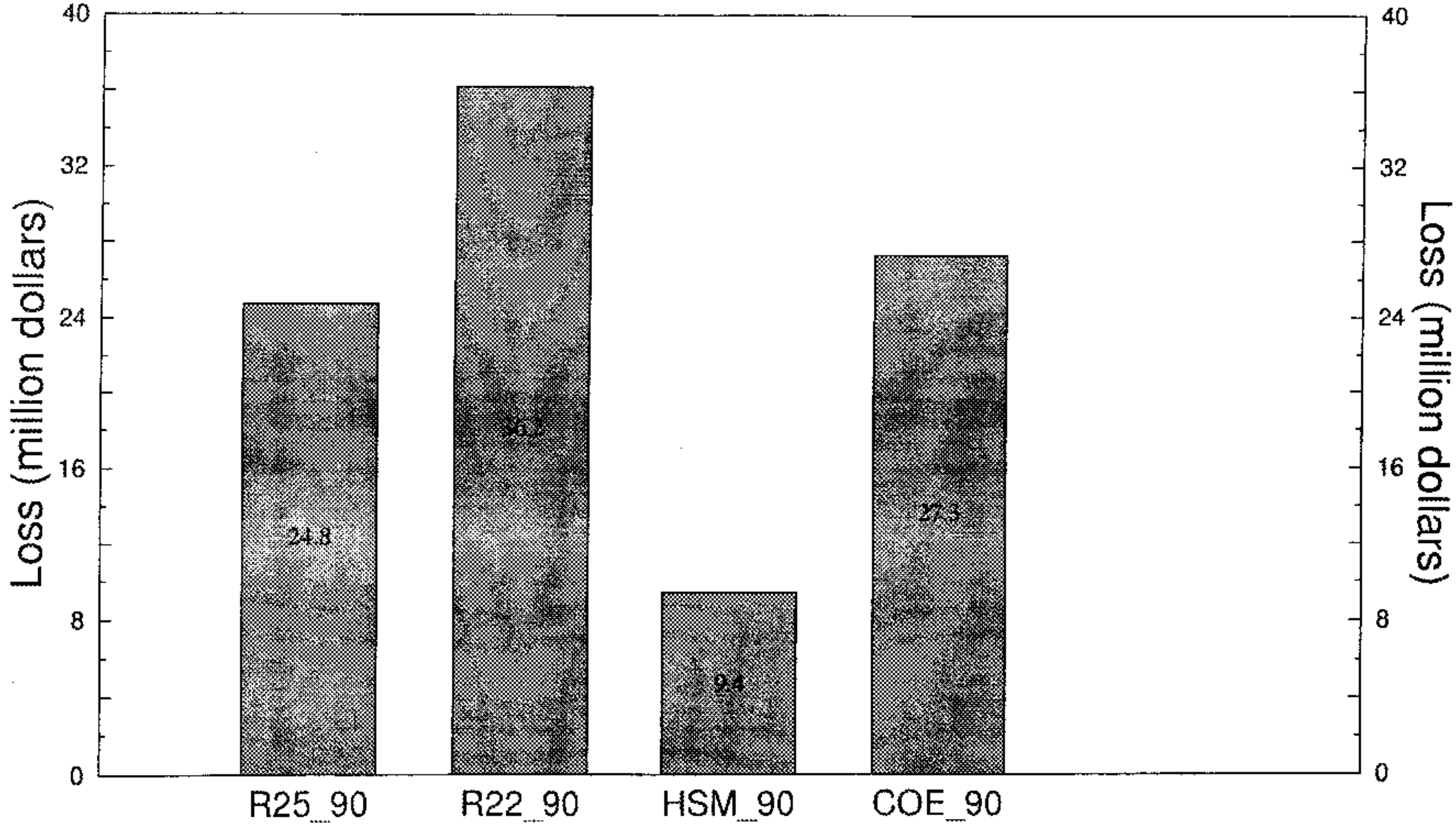
Total EAA/LOSA Irrigation Demands and Demands Not Met

for the 1965 – 1995 Simulation Period



*Other Lake Service SubAreas Outside the Plan Boundaries (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

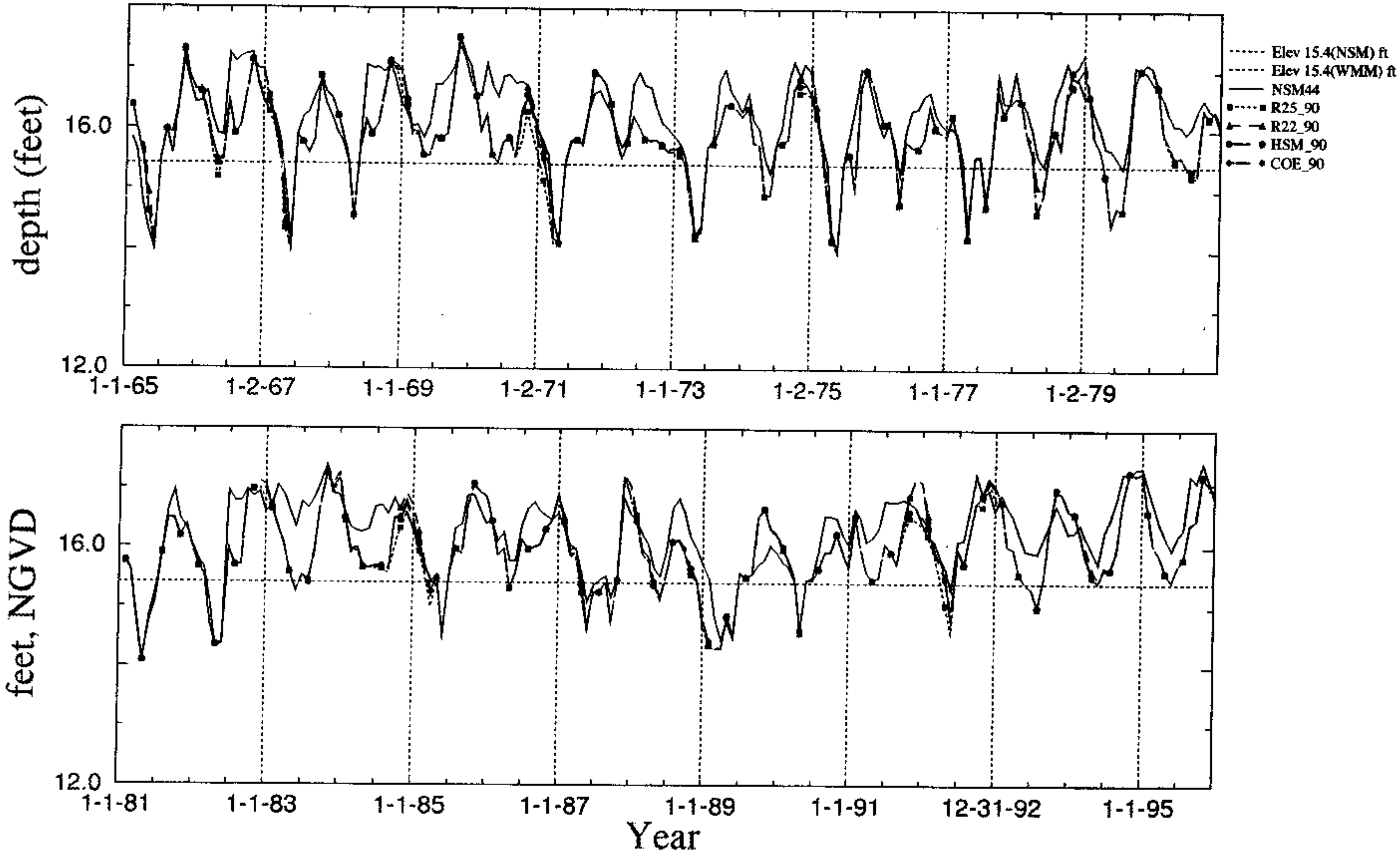
EAA IRRIGATED AREA ECONOMIC LOSSES
Total Losses Due to ET Reduction for 31 yr. simulation



Note: Losses are based on Yield Reductions for Sugarcane in the EAA.

Performance Measures for the
Everglades WCAs

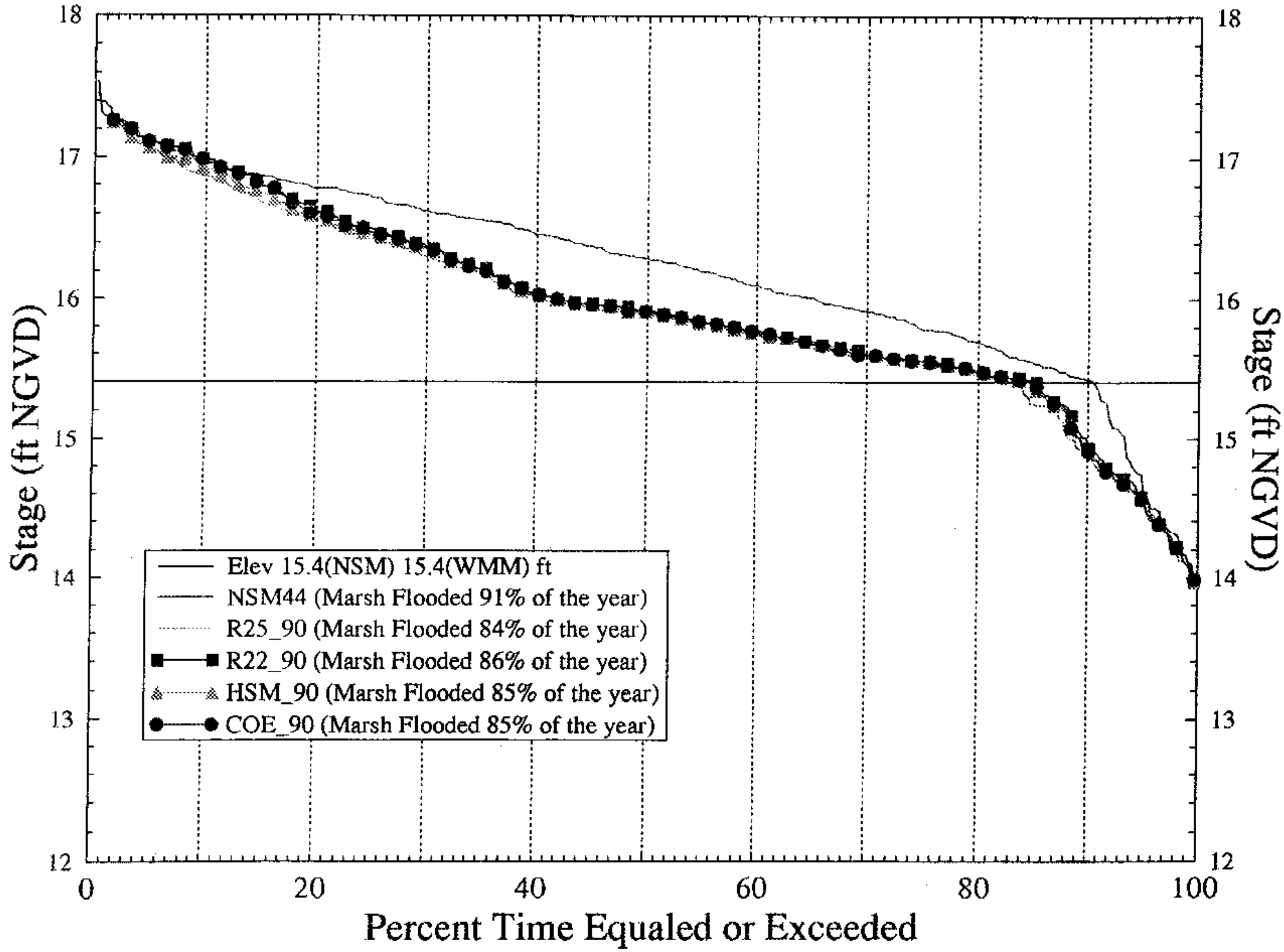
Stage Hydrograph at Central Portion of WCA-1
(Gage 1-7, Cell R48 C31)



Wed Apr 30 12:08:41 1997

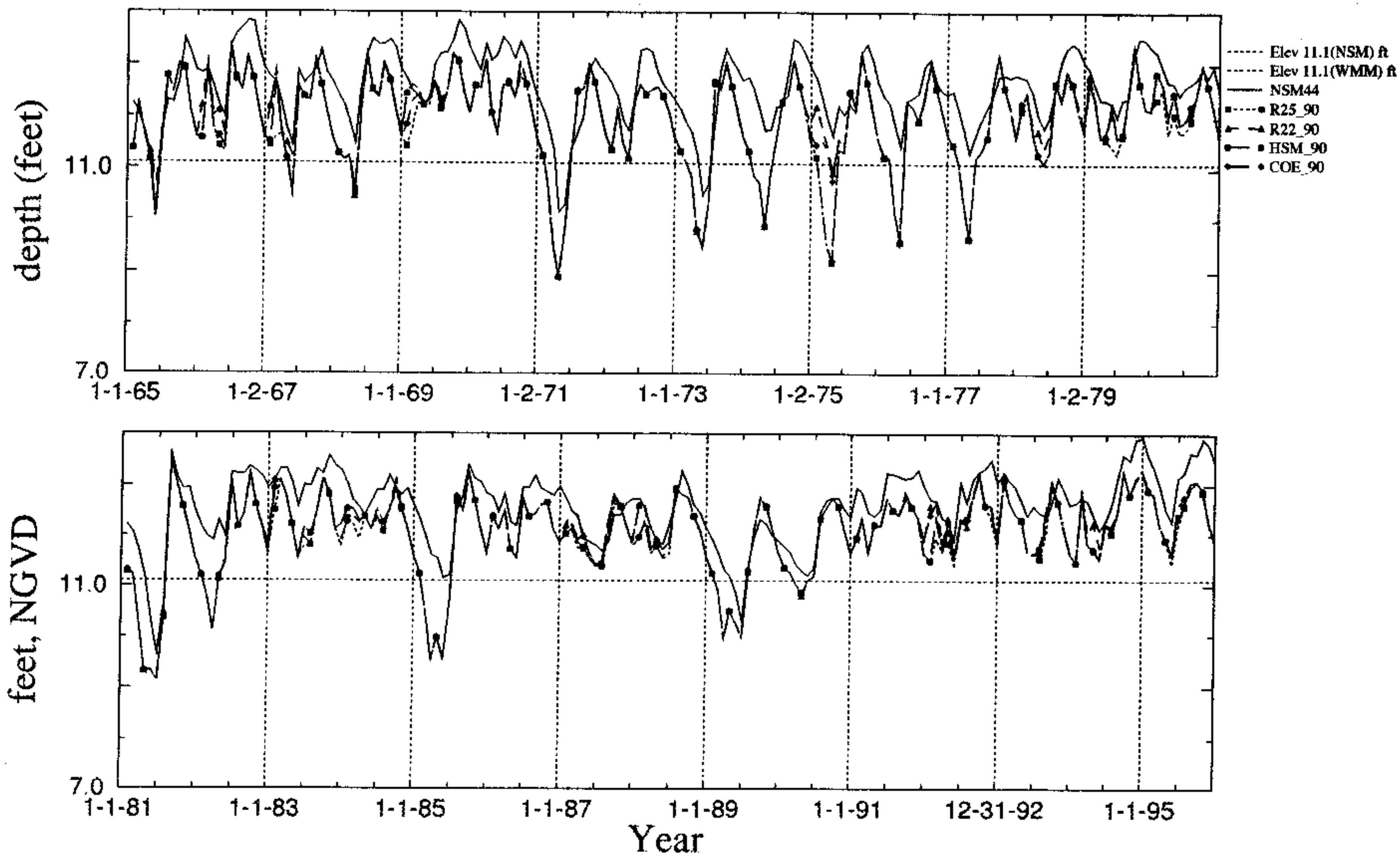
SFWMM Simulation

Stage Duration Curves at Central Portion of WCA-1 (Gage 1-7, Cell R48 C31)



C-18

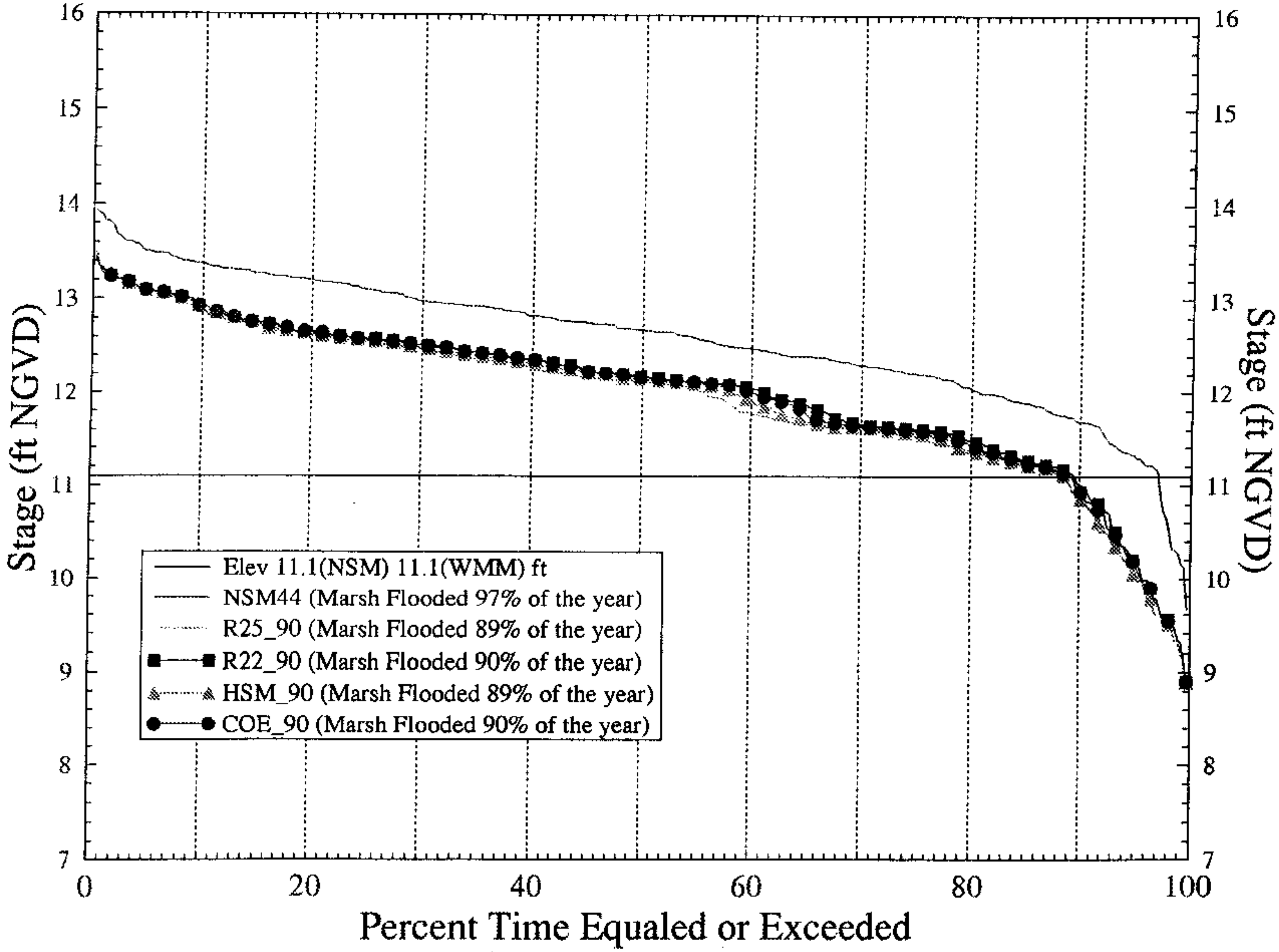
Stage Hydrograph for Central Portion of WCA-2A
(Gage 2-17, Cell R40 C29)



Wed Apr 30 12:06:56 1997

SFWMM Simulation

Stage Duration Curves at Central Portion of WCA-2A (Gage 2-17, Cell R40 C29)

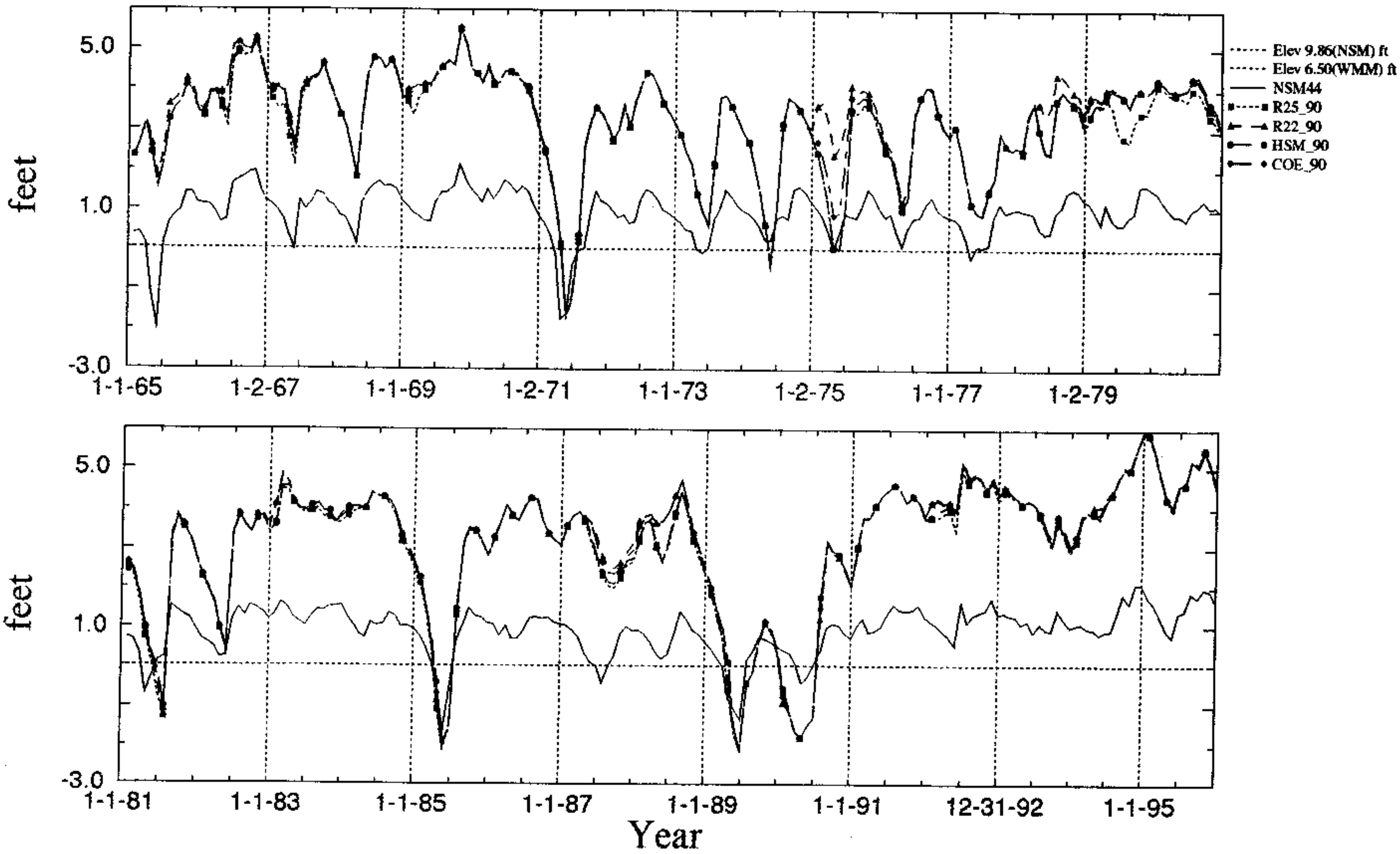


2-)

Wed Apr 30 12:00:21 1997

Environmental, Level II, WCA
SFWMM Simulation

Normalized Stage Hydrograph at South End of WCA-2B (Gage 2B-21, R35 C30)



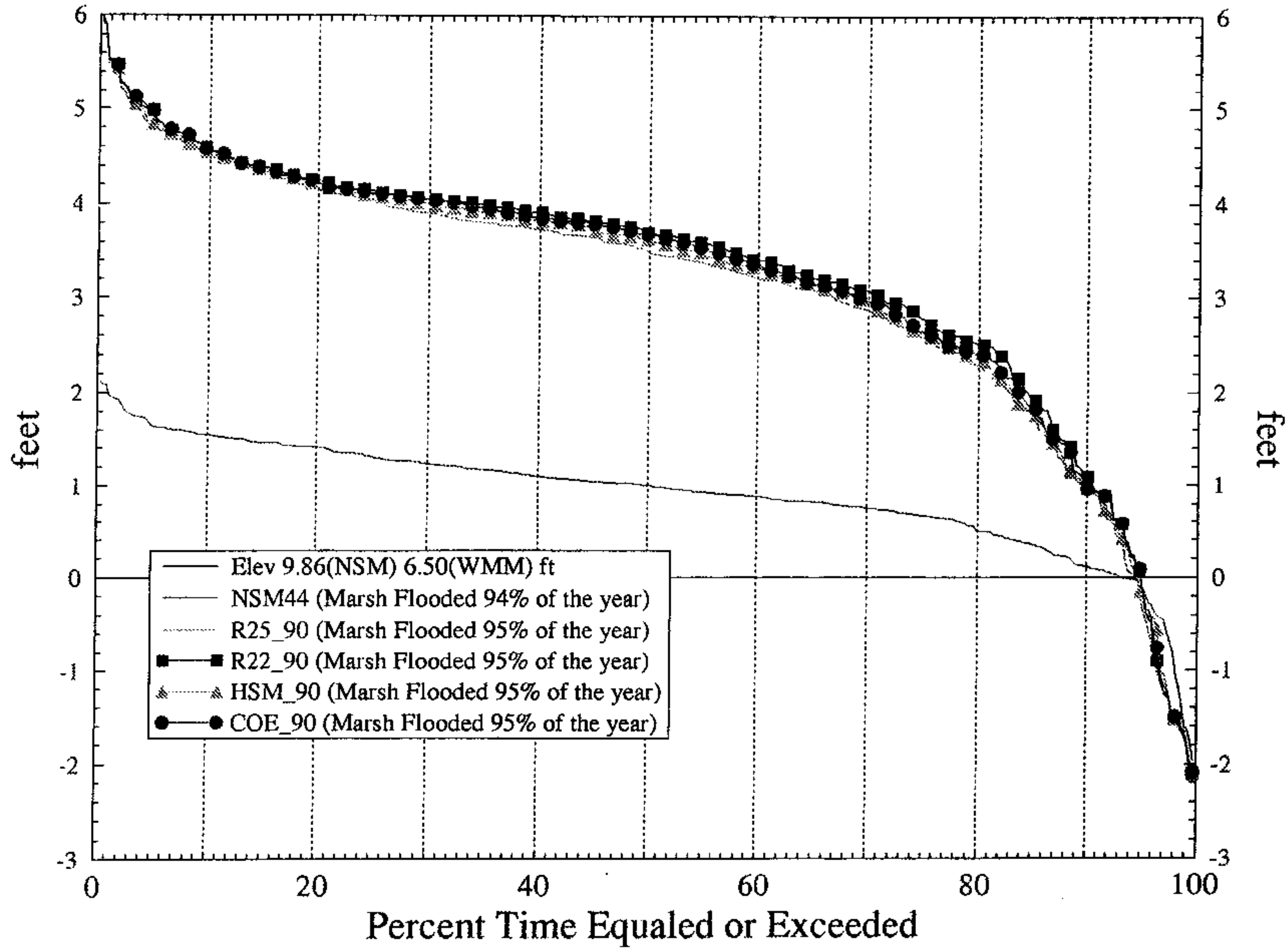
Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Wed Apr 30 12:31:33 1997

SFWMM Simulation

C-21

Normalized Stage Duration Curves at South End of WCA-2B (Gage 2B-21, R35 C30)

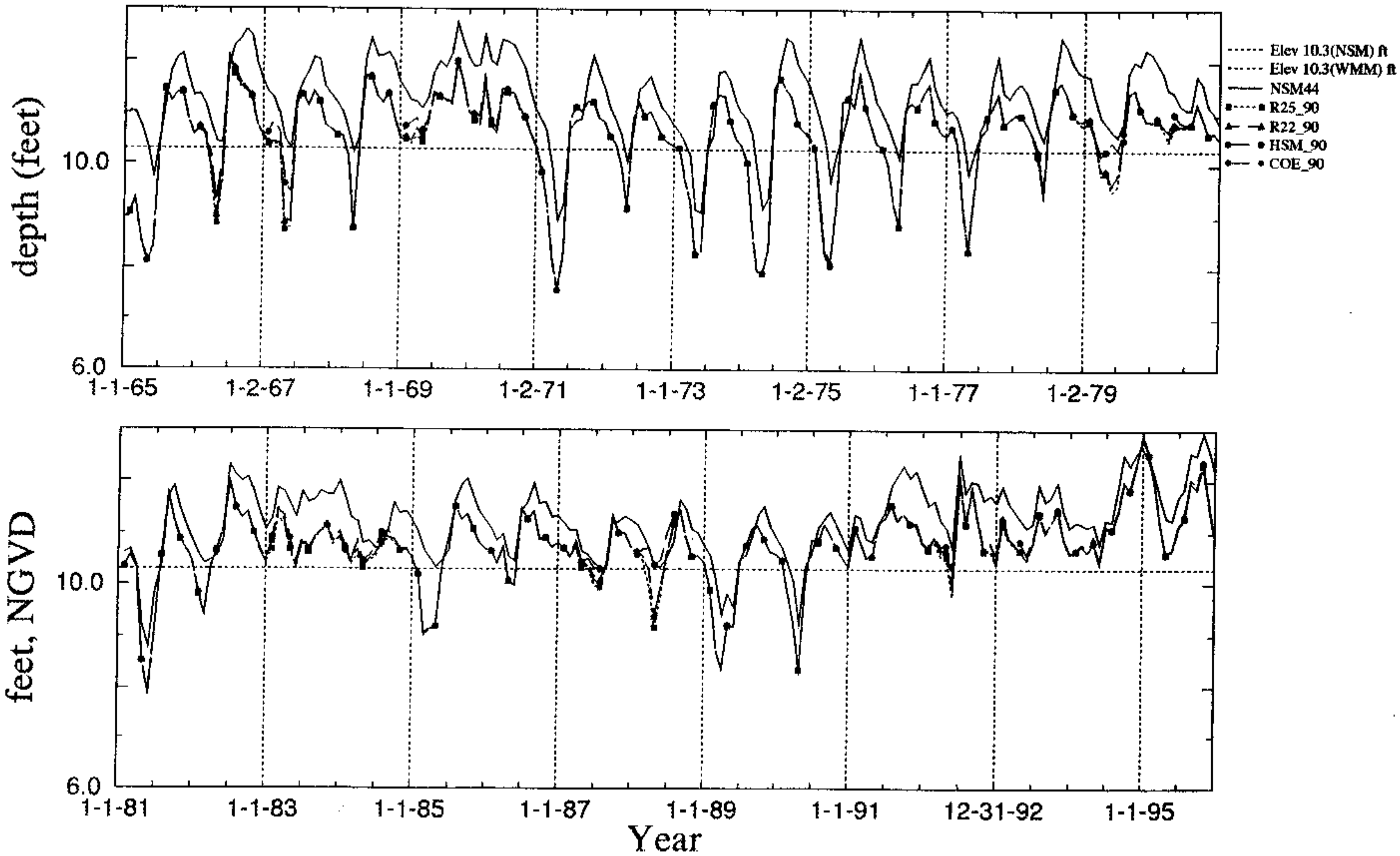


Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Wed Apr 30 12:32:01 1997

Environmental, Level II, WCA SFWMM Simulation

Stage Hydrograph for North End of WCA-3A
(Gage 3A-2, West of Miami Canal, R36 C18)

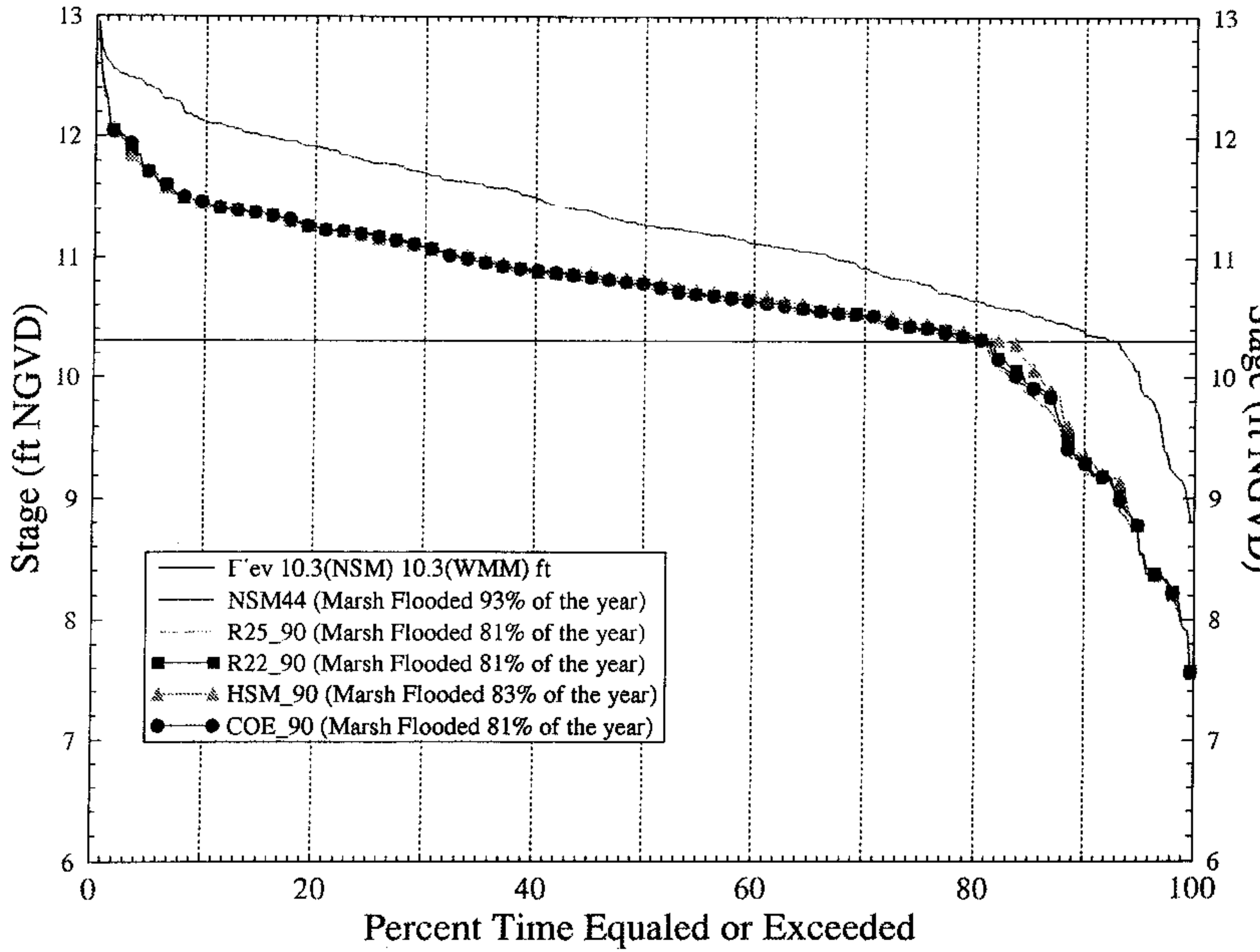


C-23

Wed Apr 30 12:07:13 1997

Environmental/WCA/EDR
SFWMM Simulation

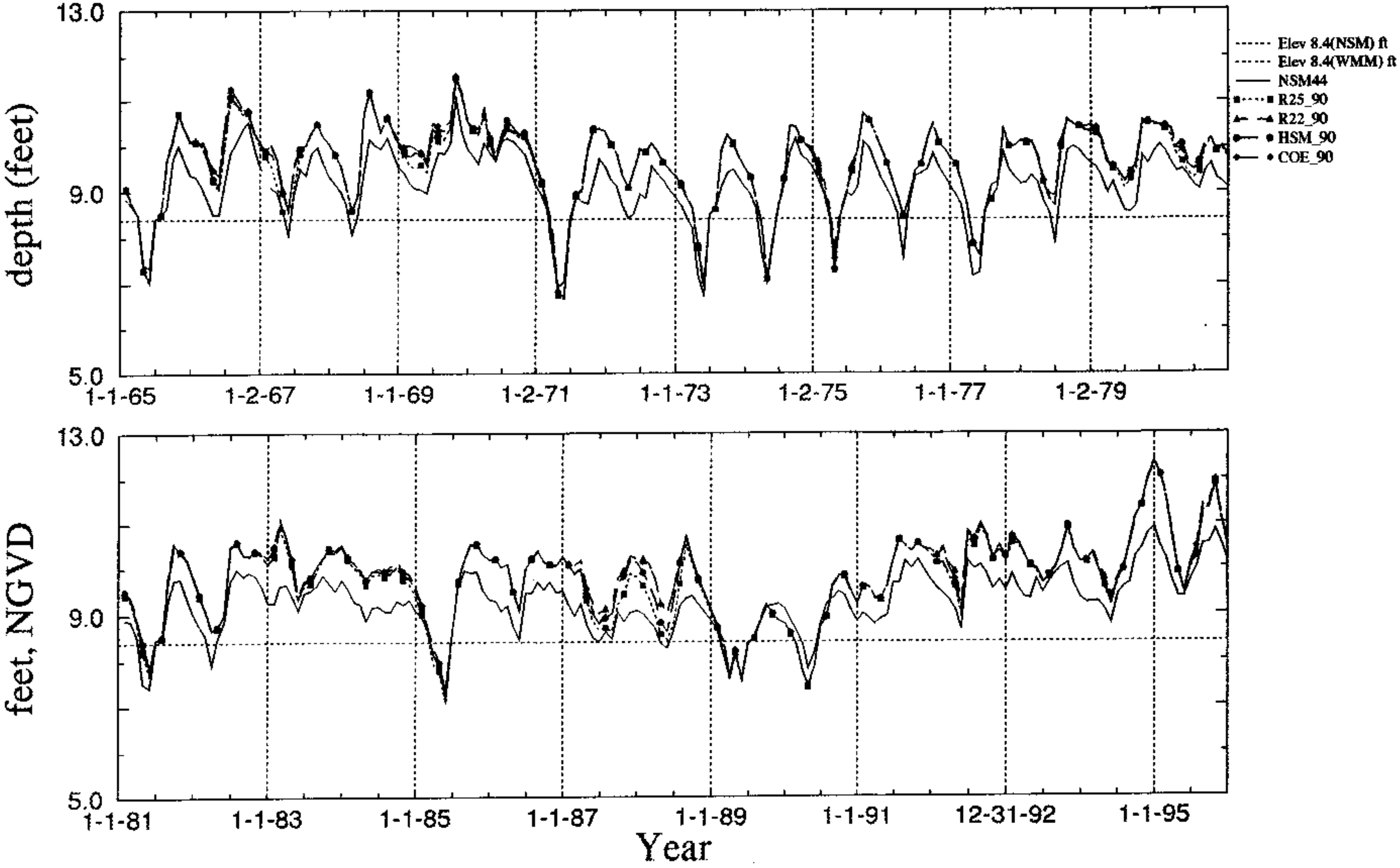
Stage Duration Curves at North End of WCA-3A
(Gage 3A-2, Cell R36 C18, West of Miami Canal)



Wed Apr 30 12:00:45 1997

Environmental, Level II, WCA

Stage Hydrograph for Central Portion of WCA-3A
(Gage 3A-4, Cell R29 C21)

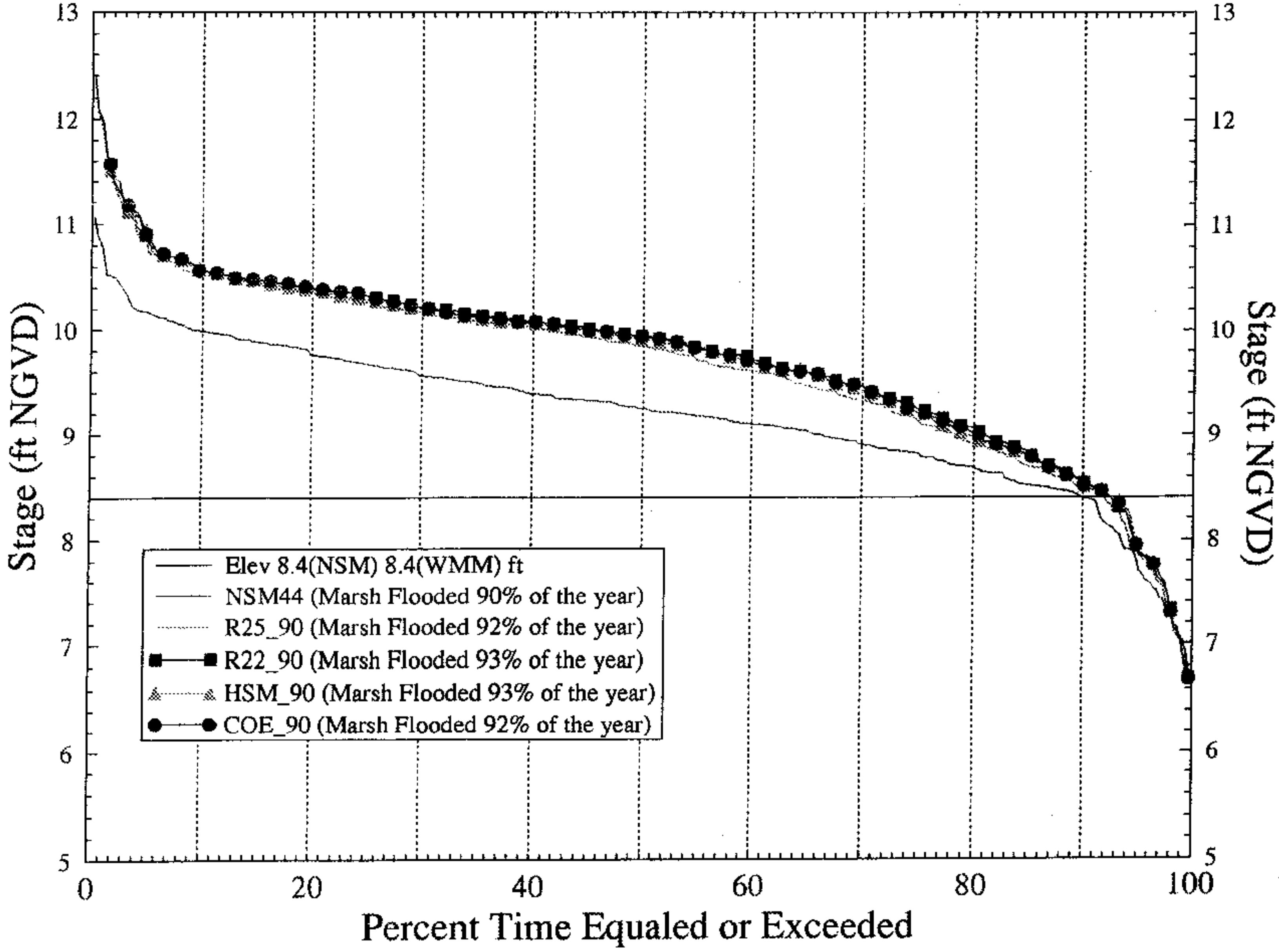


C-25

Wed Apr 30 12:07:37 1997

SFWMM Simulation

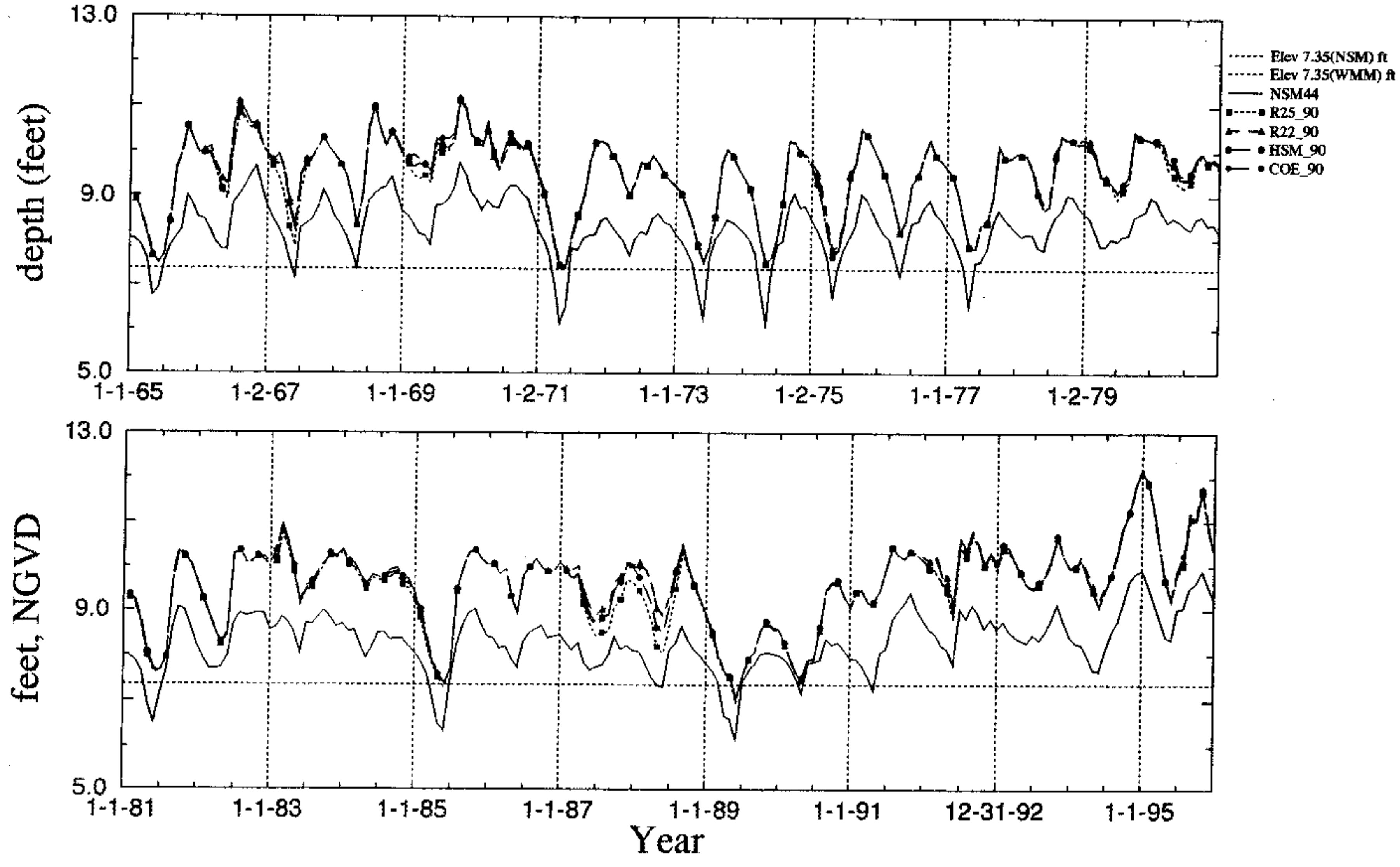
Stage Duration Curves at Central Portion of WCA-3A (Gage 3A-4, Cell R29 C21)



Wed Apr 30 12:01:26 1997

Environmental, Level II, WCA
SFWMM Simulation

Stage Hydrograph for South End of WCA-3A (Gage 3A-28, Cell R24 C19)

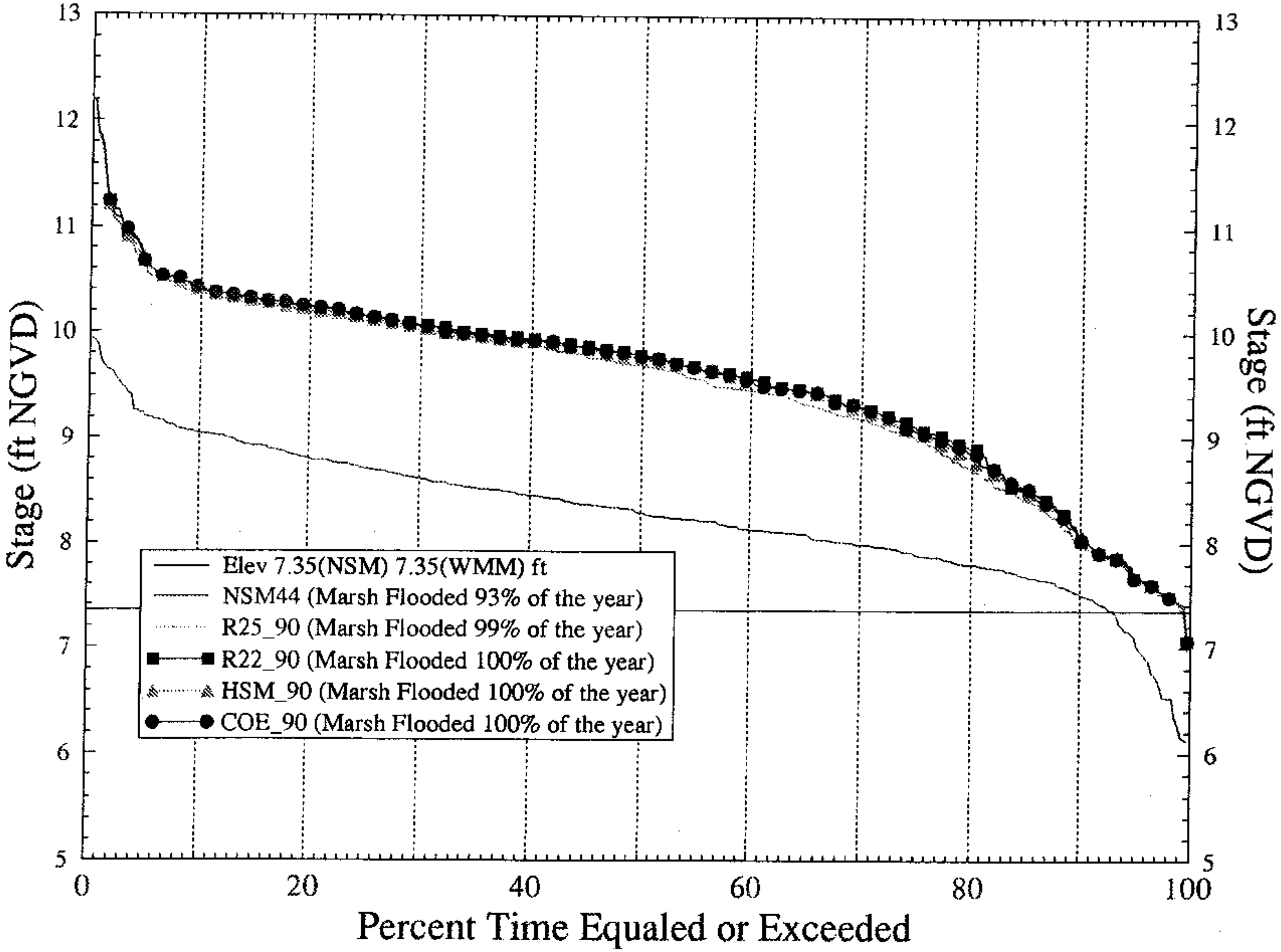


Wed Apr 30 12:07:25 1997

Environmental Env WCA/EIR
SFWMM Simulation

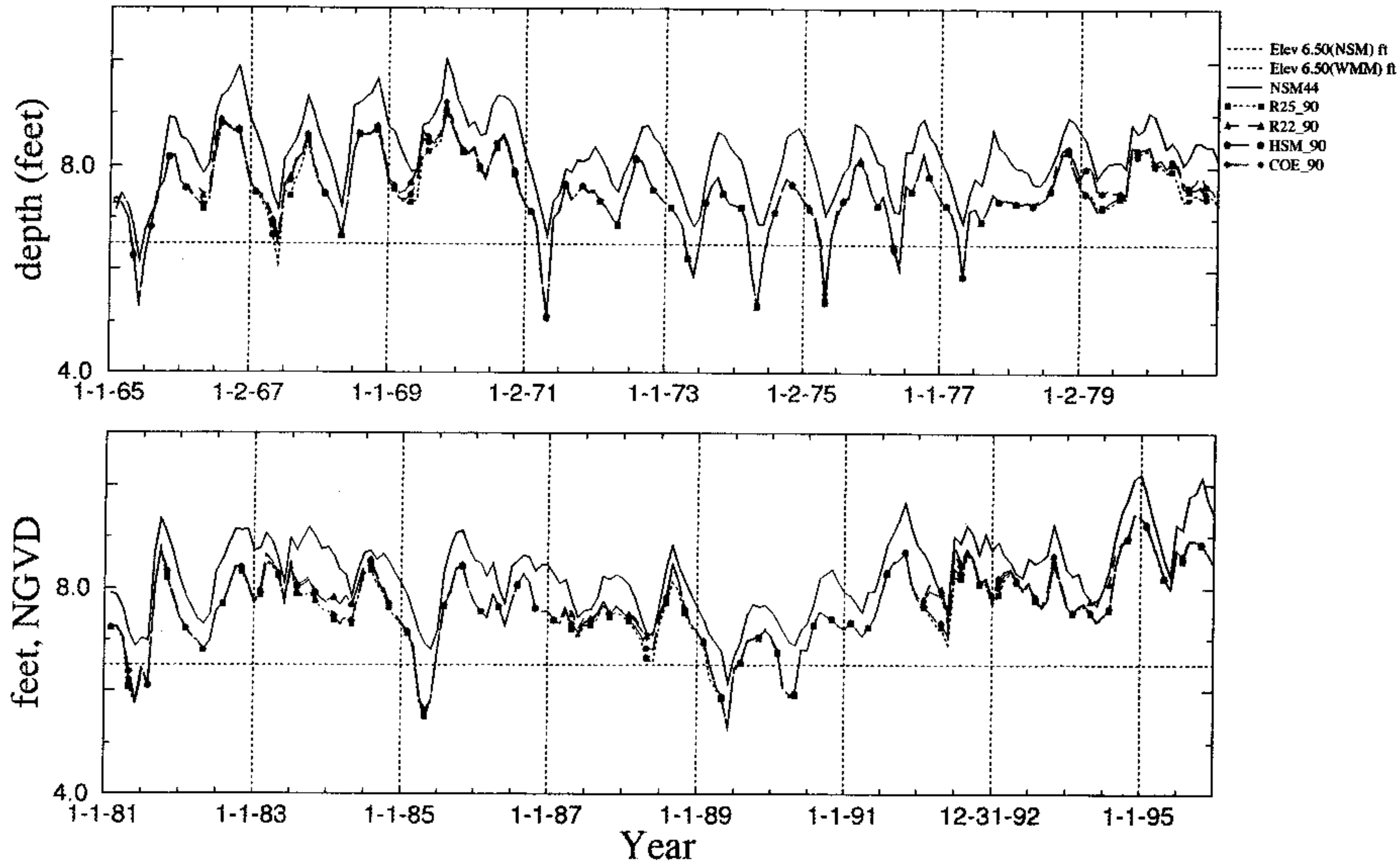
C-27

Stage Duration Curves at South End of WCA-3A
(Gage 3A-28, Cell R24 C19)



C-28

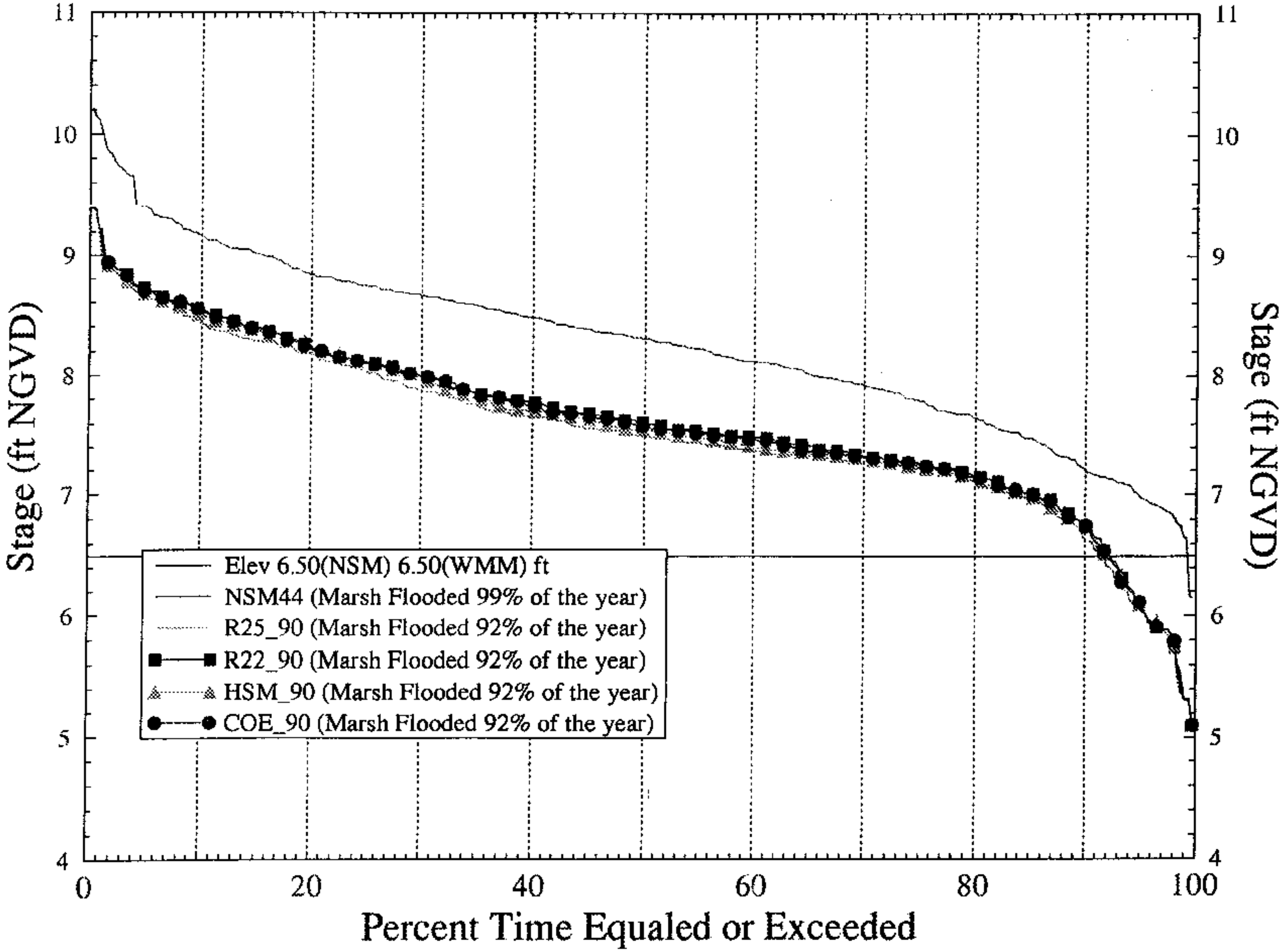
Stage Hydrograph for North-End of WCA-3B
(Gage 3B-2, Cell R25 C25)



Wed Apr 30 12:07:58 1997

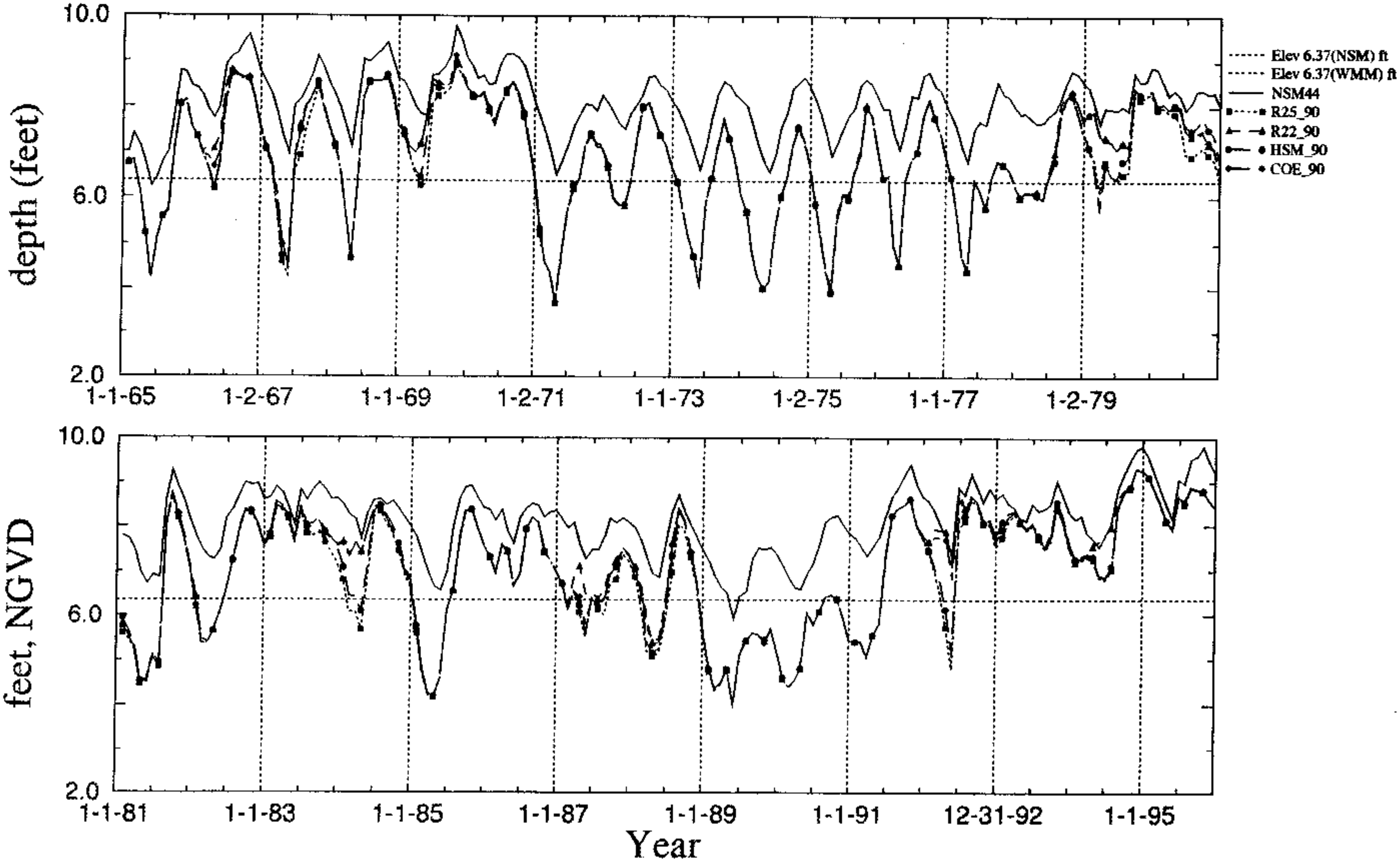
Environmental, WCA/ENR
SFWMM Simulation

Stage Duration Curves at North-End of WCA-3B
(Gage 3B-2, Cell R25 C25)



C-3c

Stage Hydrograph for South End of WCA-3B
(Gage 3B-SE, Cell R23 C26)

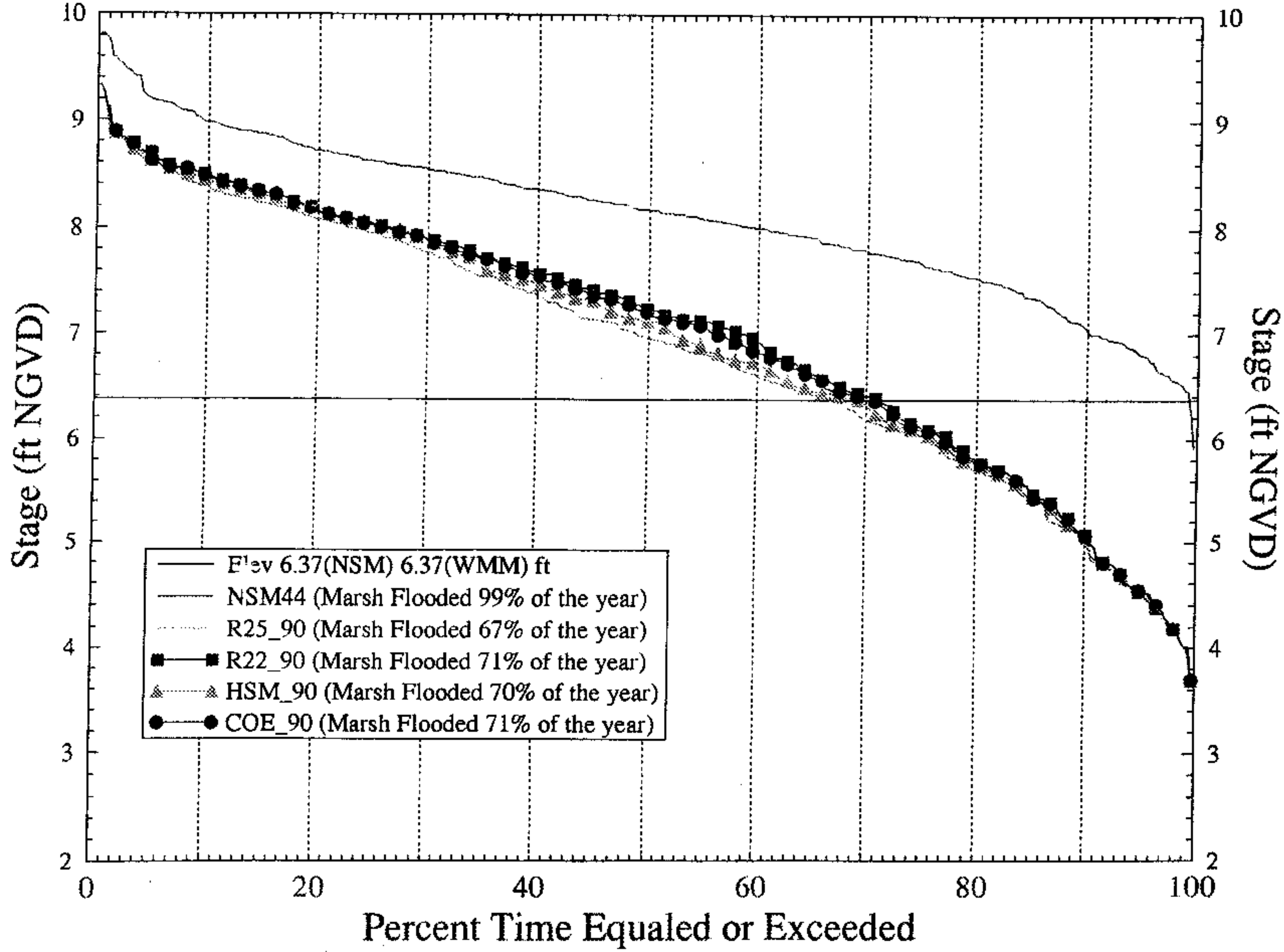


C-31

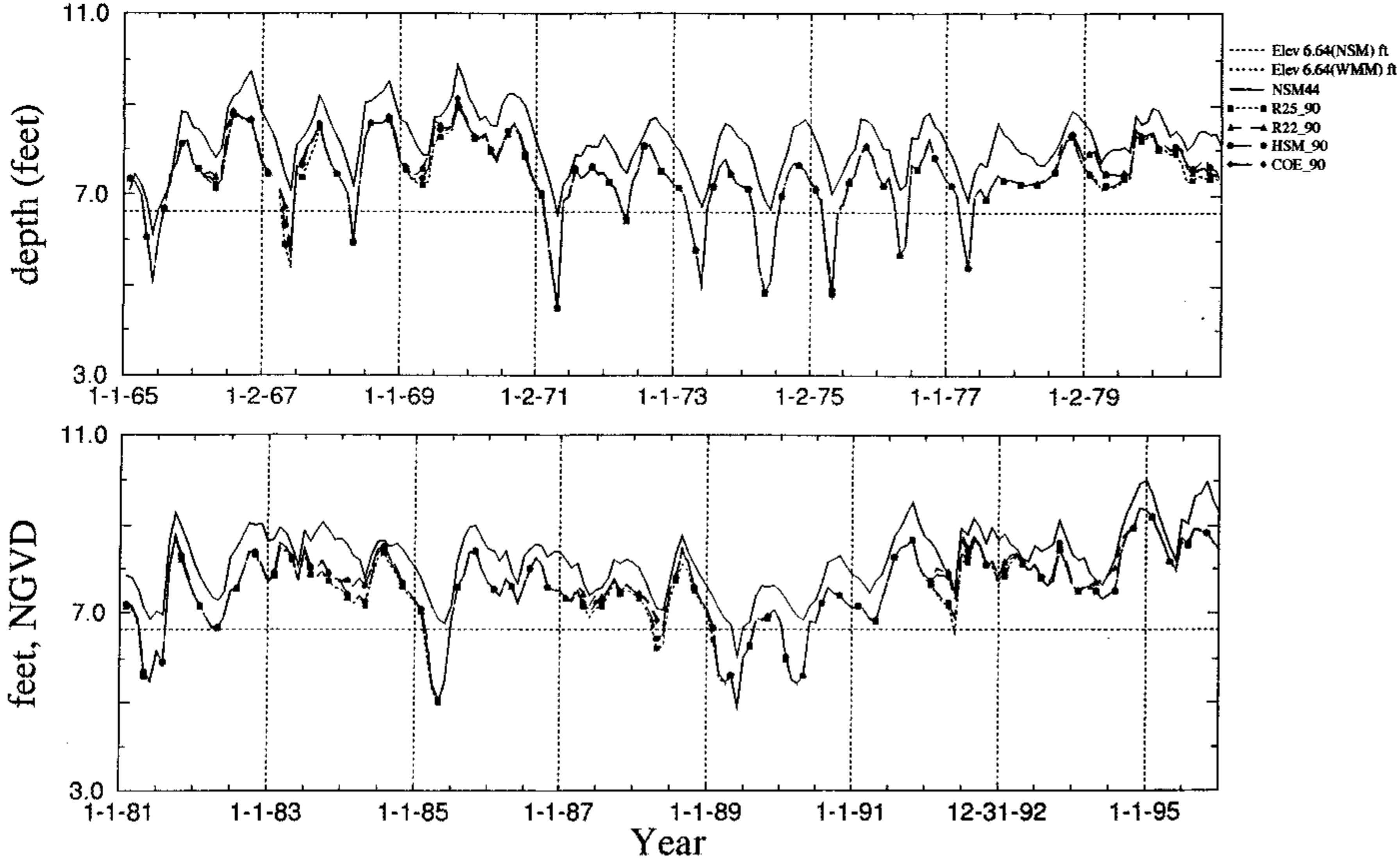
Wed Apr 30 12:08:24 1997

Environmental, Level, WCA, ZDR
SFWMM Simulation

Stage Duration Curves at South End of WCA-3B
(Gage 3B-SE, Cell R23 C26)



Stage Hydrograph at South End of WCA-3B
(Cell R24 C25)

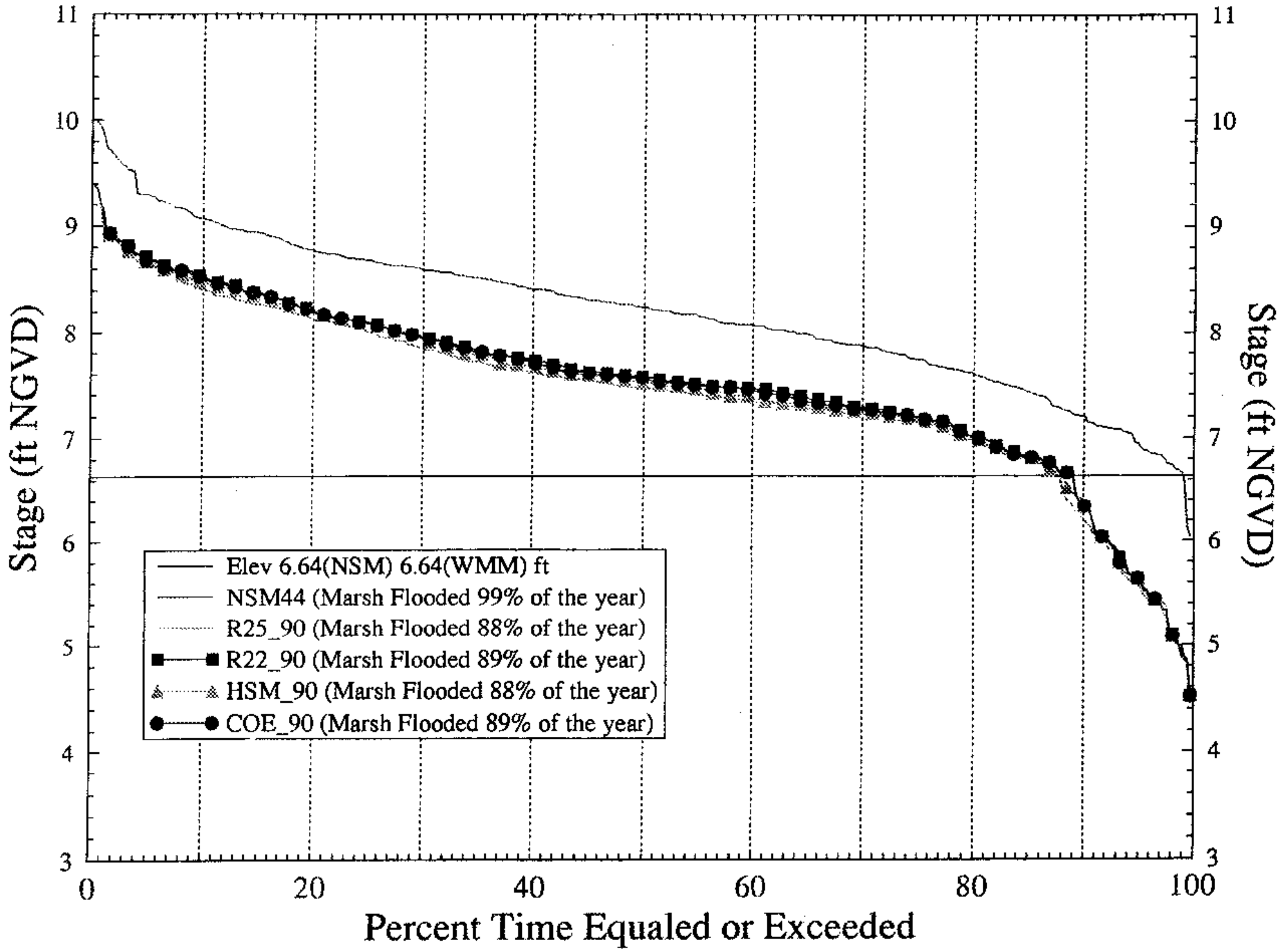


C-33

Wed Apr 30 12:08:10 1997

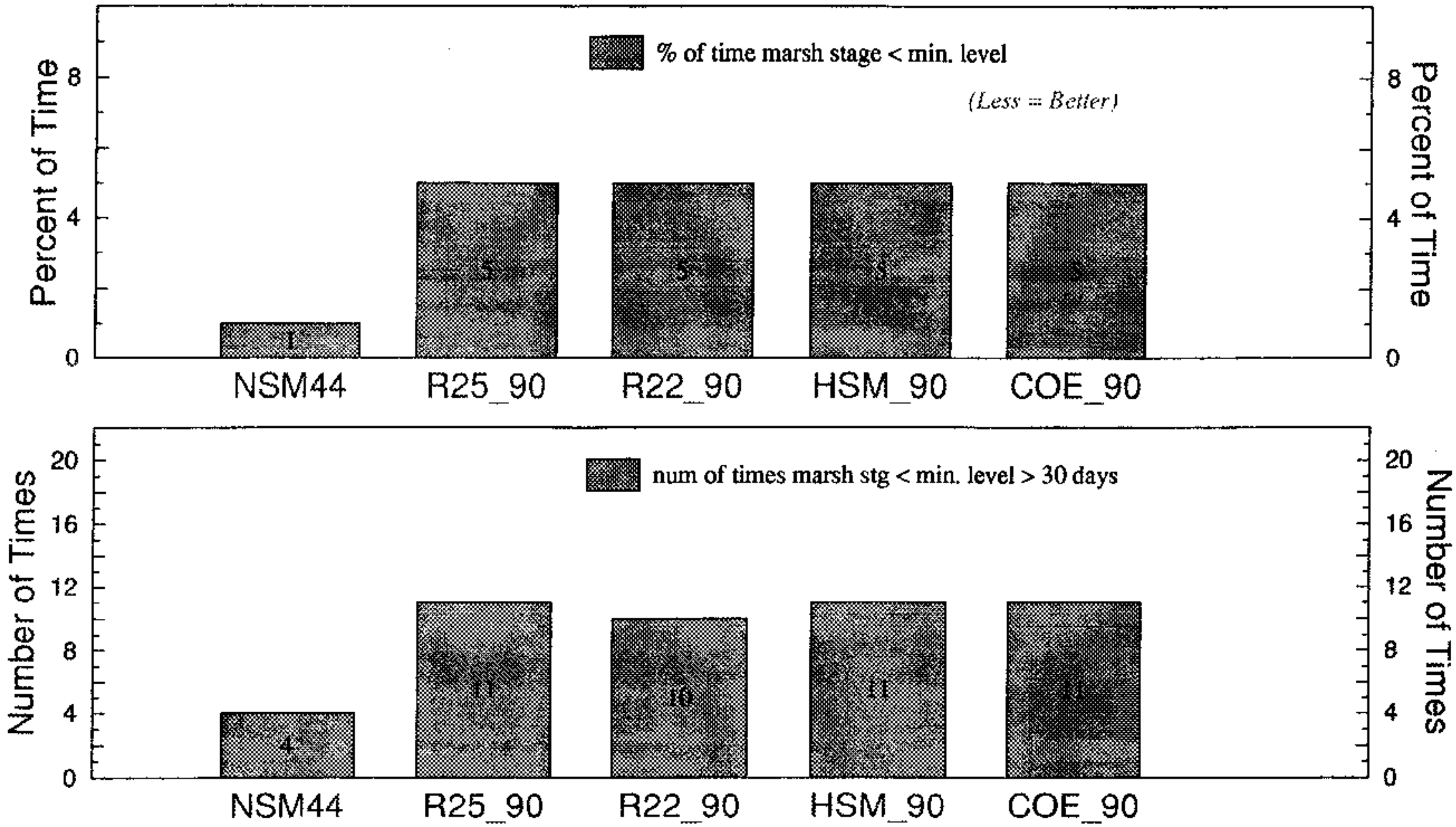
SFWMM Simulation

Stage Duration Curves at South End of WCA-3B
(Cell R24 C25)

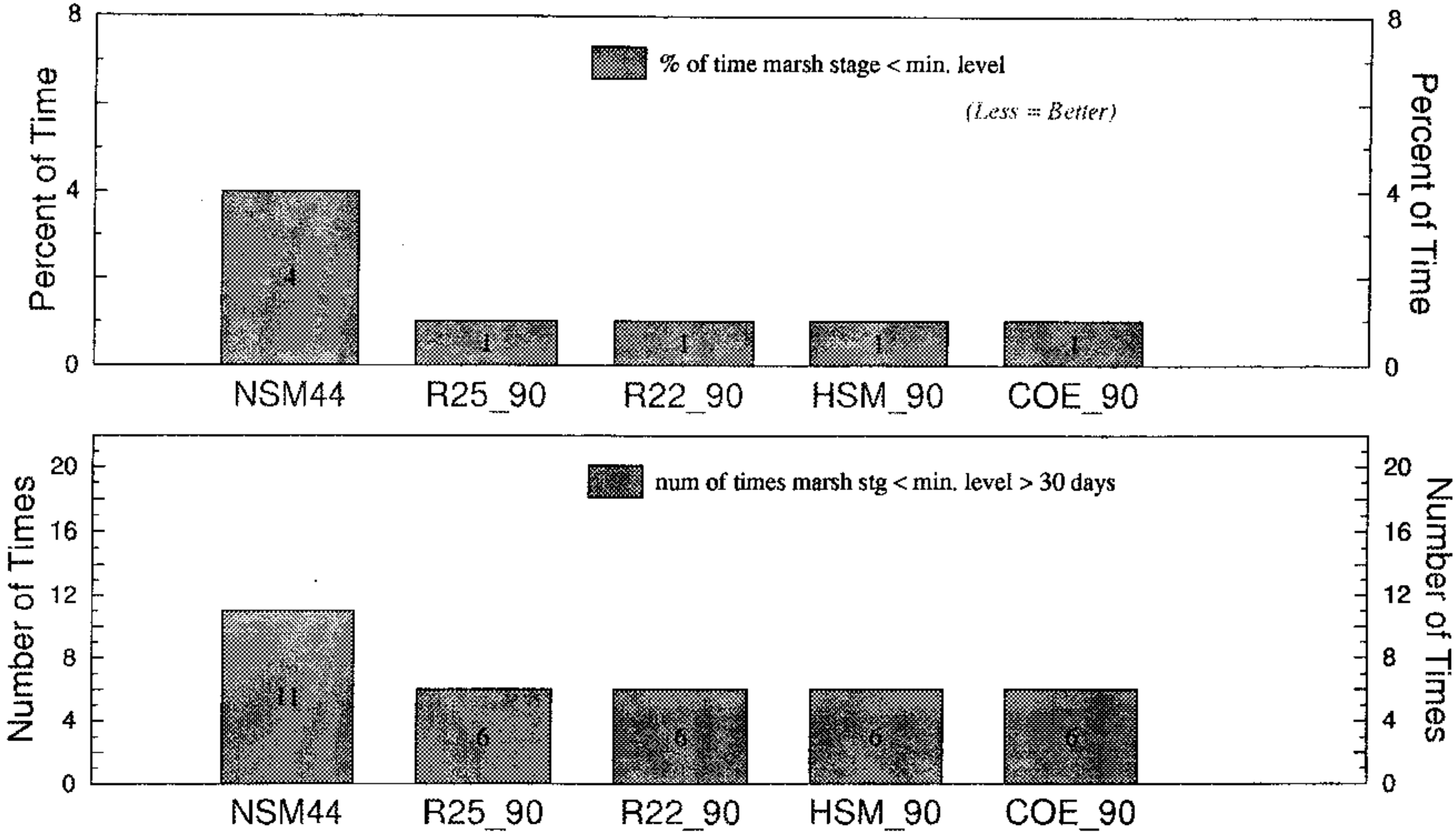


C-34

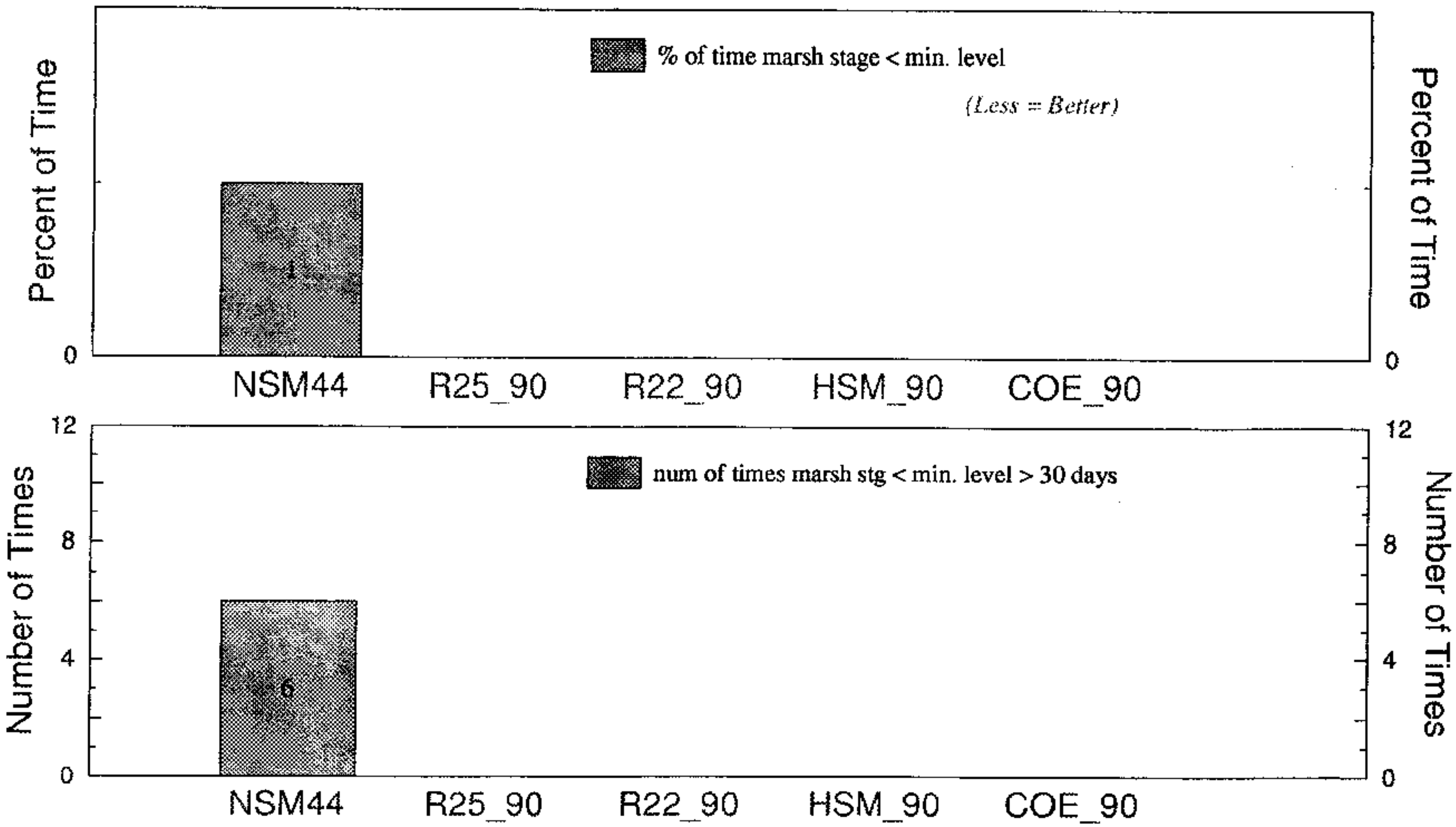
% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
(Gage 2–17, Cell R40 C29, Proposed Min Lvl 1 ft below ground)



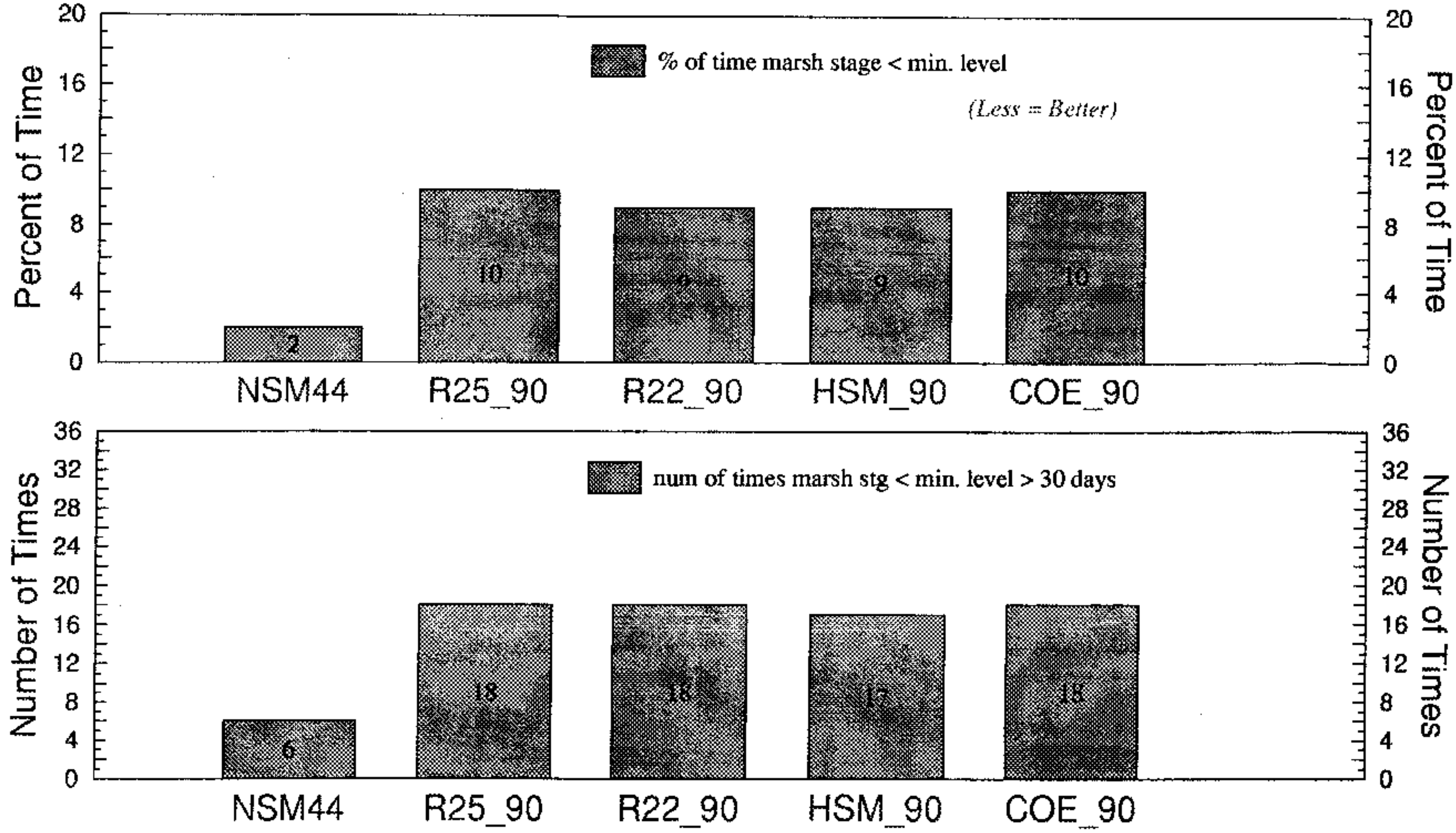
% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
Gage 3A–3, Cell R37 C25, Proposed Min Lvl 1 ft below ground



% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
(Gage 3A–28, Cell R24 C19, Proposed Min Lvl 1 ft below ground)

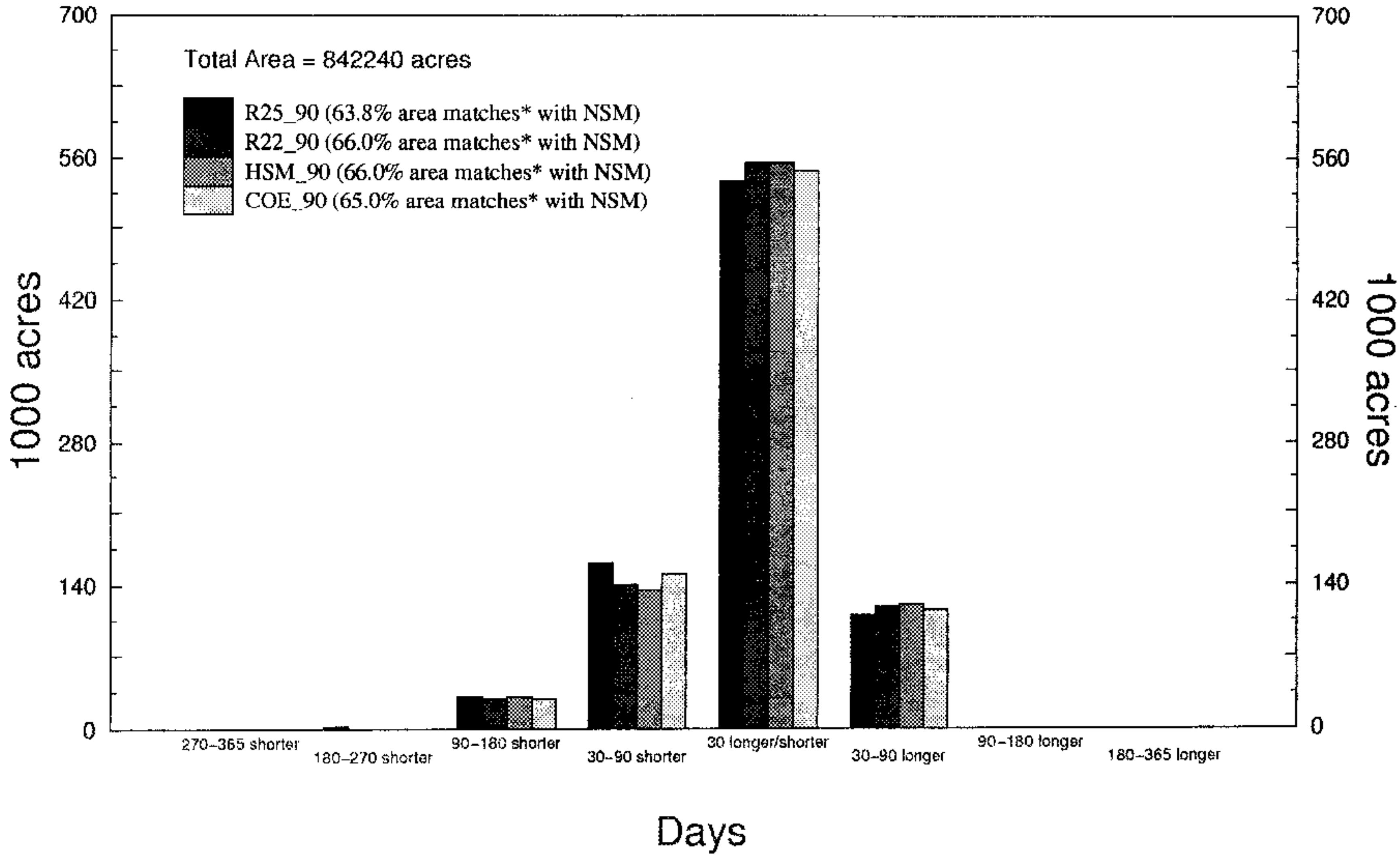


% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
(Gage 3A–2, Cell R36 C18, Proposed Min Lvl 1 ft below ground)



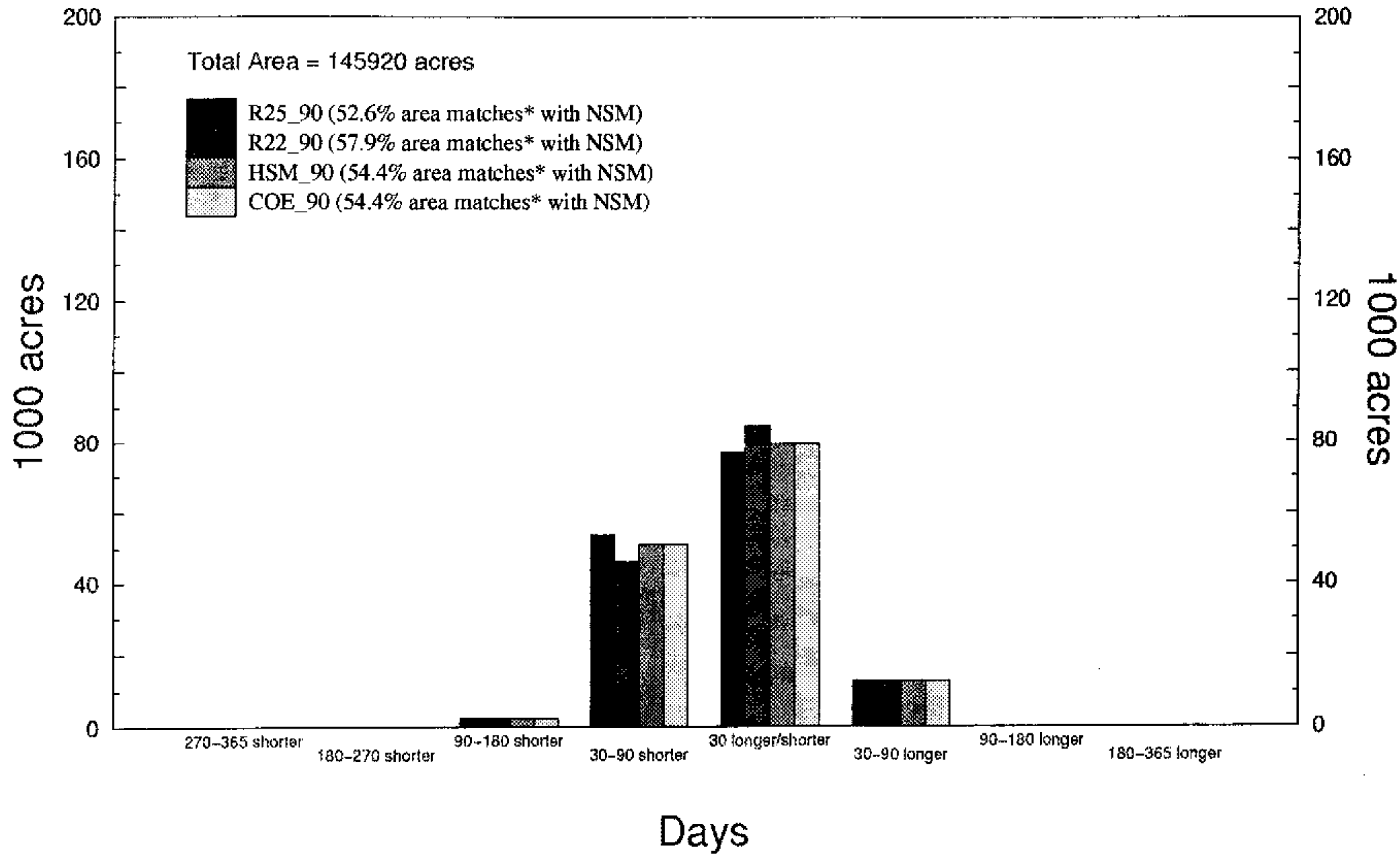
C-38

Mean NSM hydroperiod matches for the WCA SYSTEM for the 31 yr. simulation



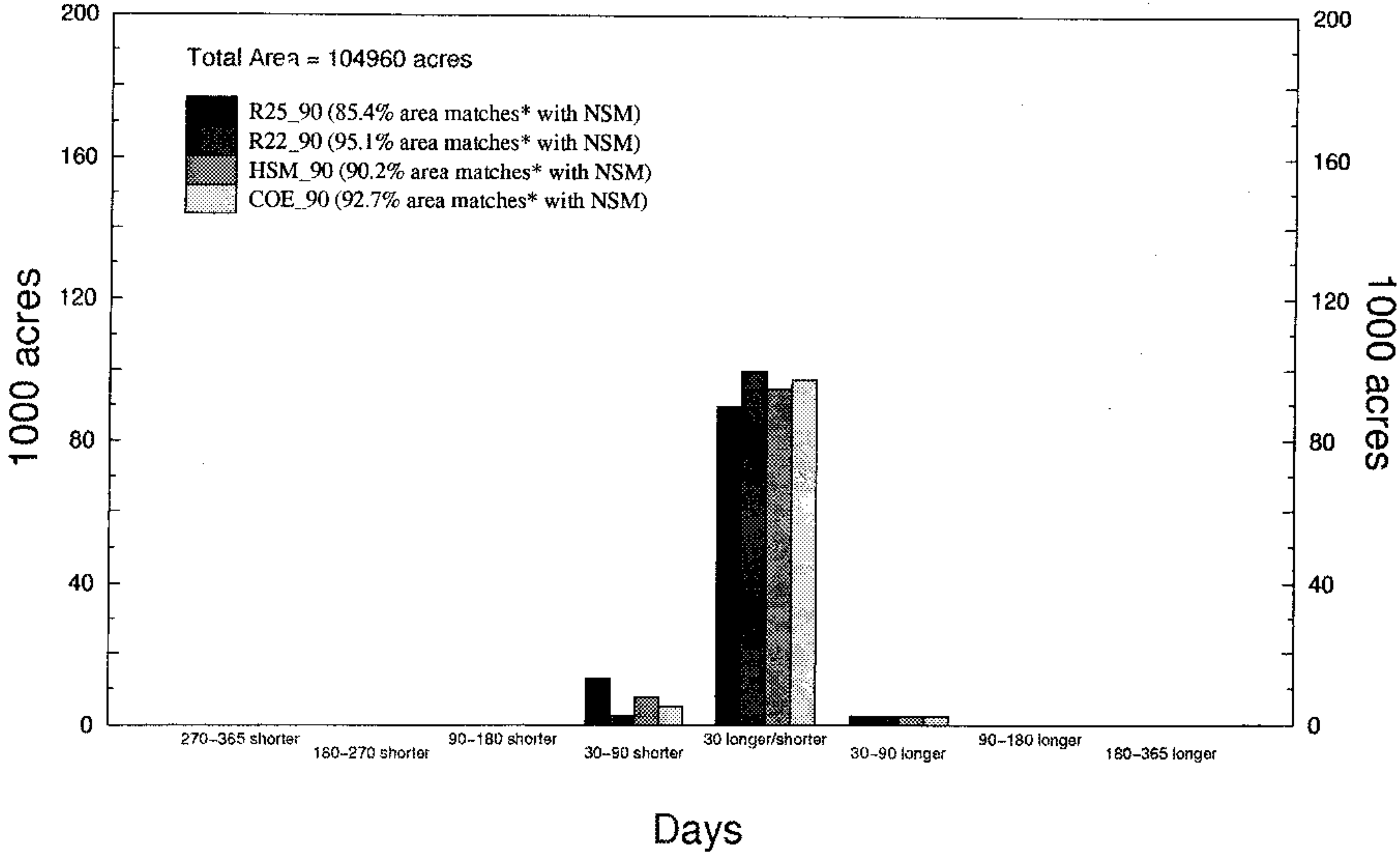
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Mean NSM hydroperiod matches for WCA–1 for the 31 yr. simulation



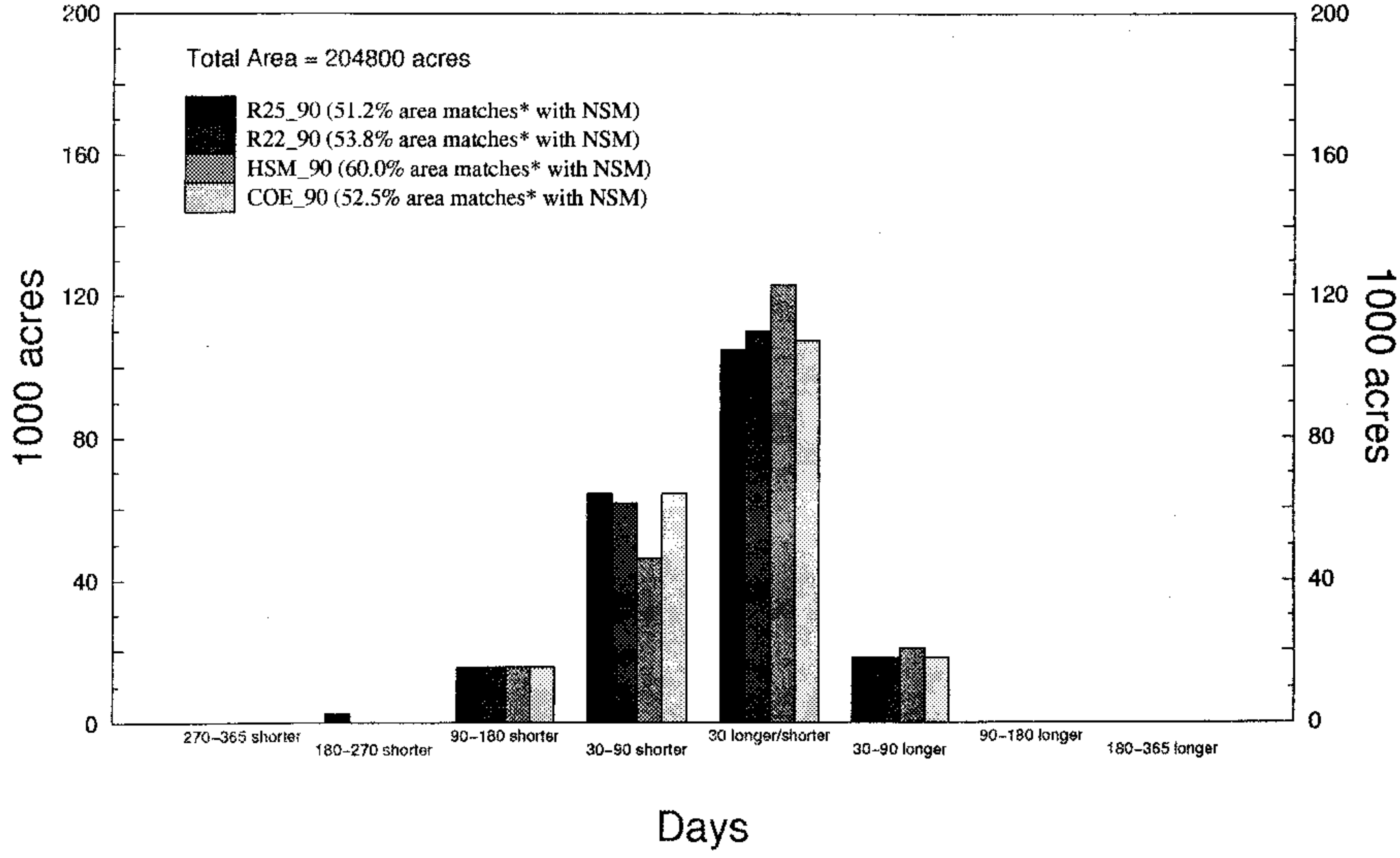
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3

Mean NSM hydroperiod matches for WCA–2A for the 31 yr. simulation



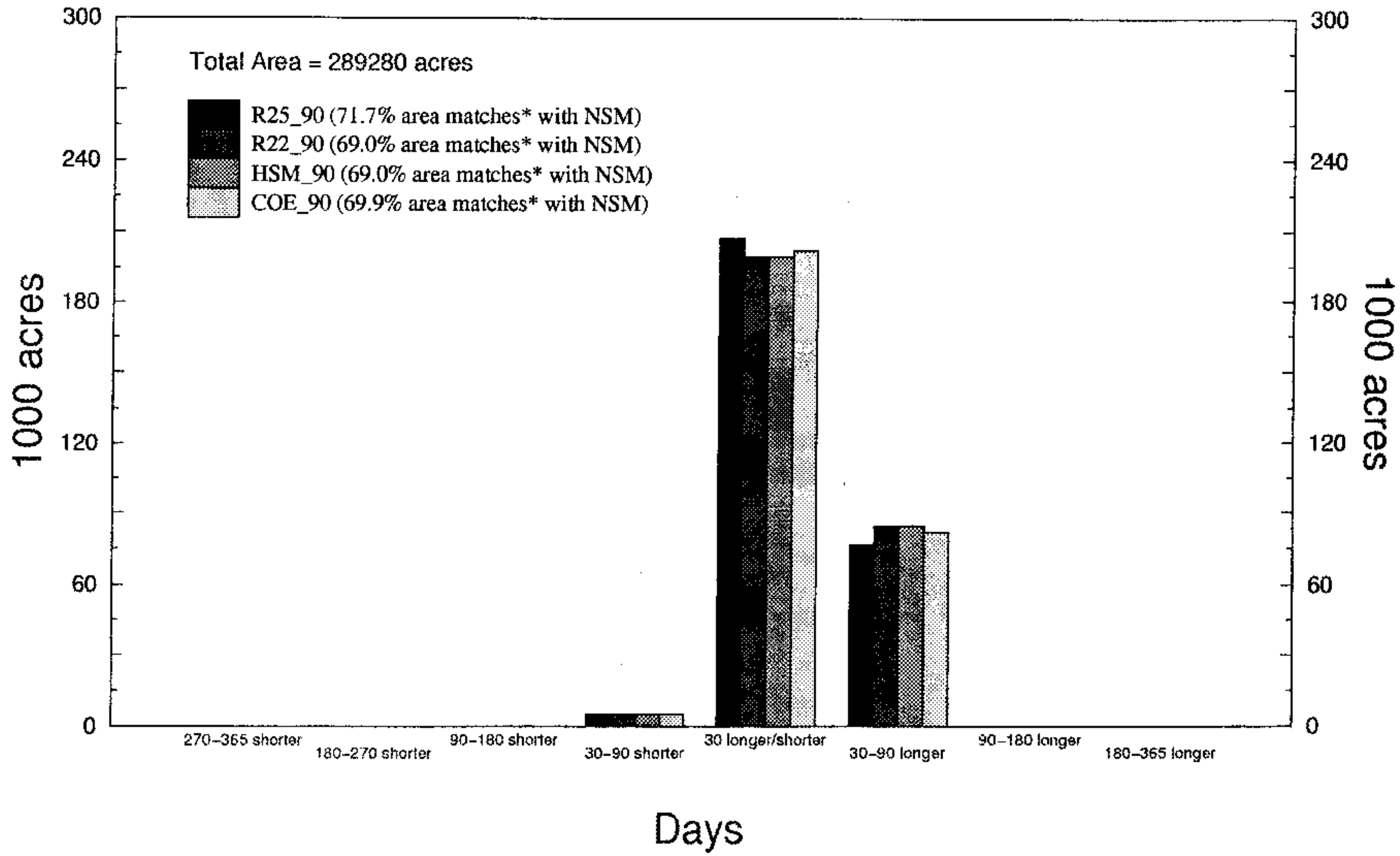
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Mean NSM hydroperiod matches for WCA–3A(North) for the 31 yr. simulation



Note: x-axis represents hydroperiod days shorter or longer as compared to NSMv4.3

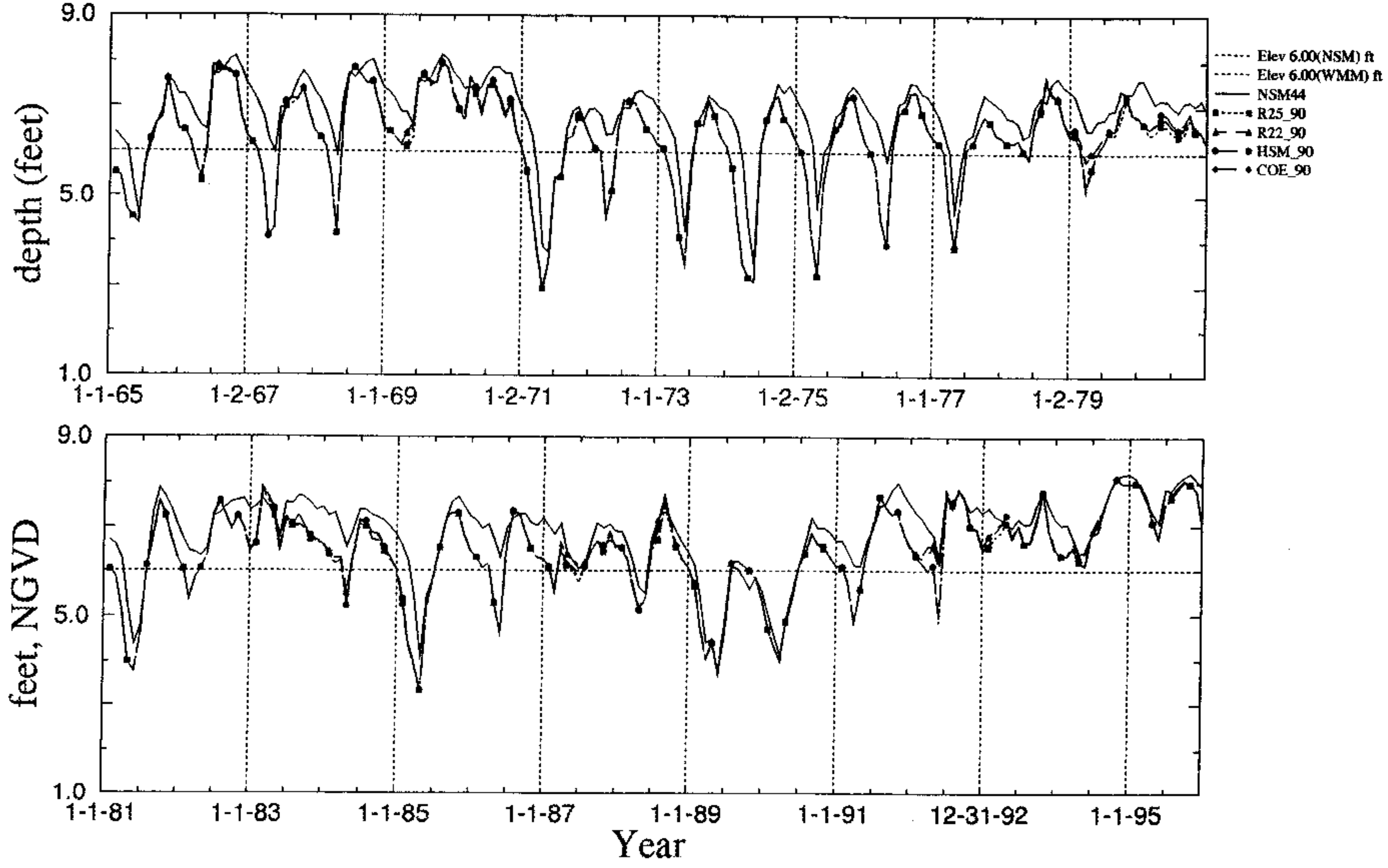
Mean NSM hydroperiod matches for WCA–3A(South) for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Performance Measures for
Everglades National Park

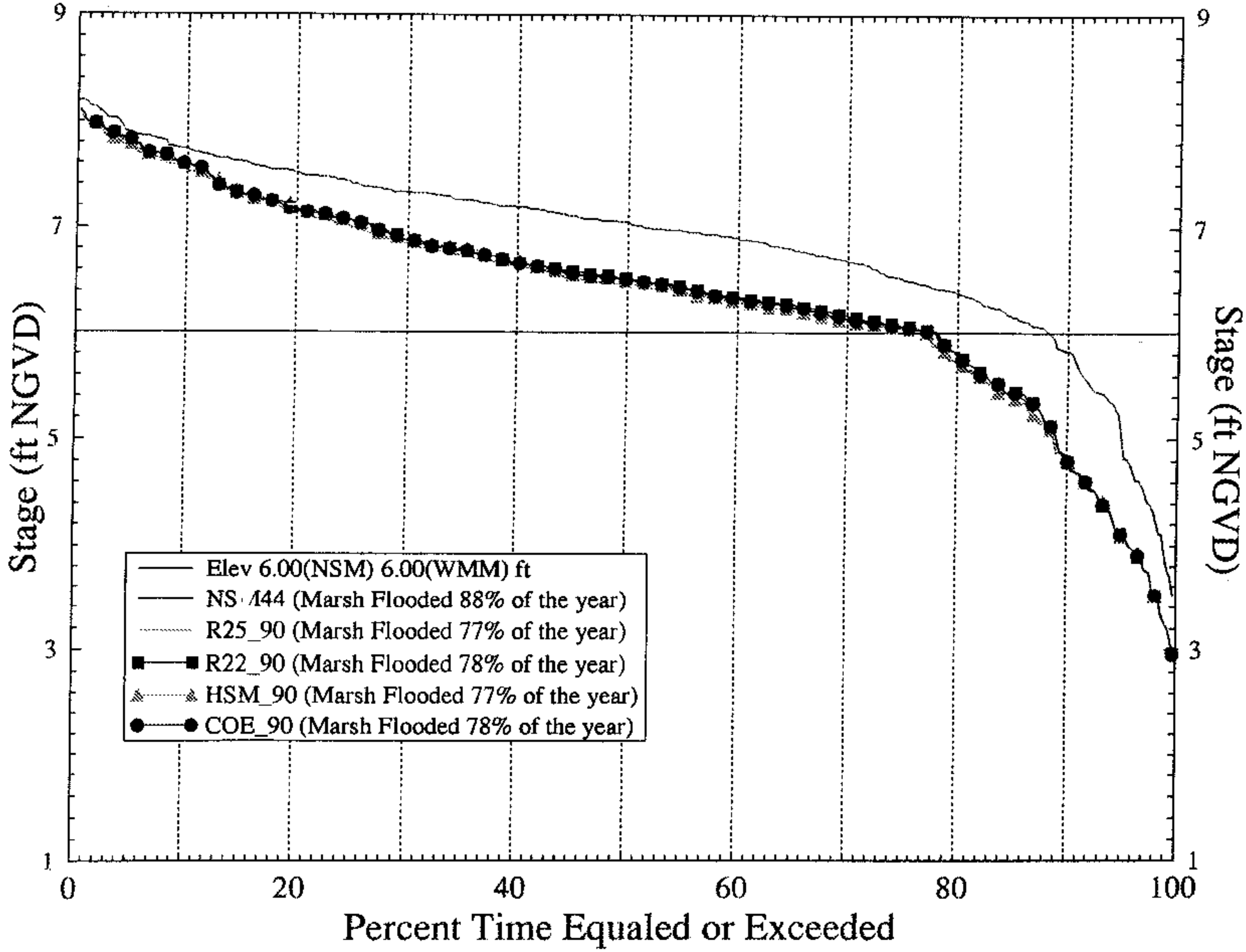
Stage Hydrograph for Marl Lands in NW SRS
Gage G-620, ENP, Cell R19 C18



Wed Apr 30 12:14:10 1997

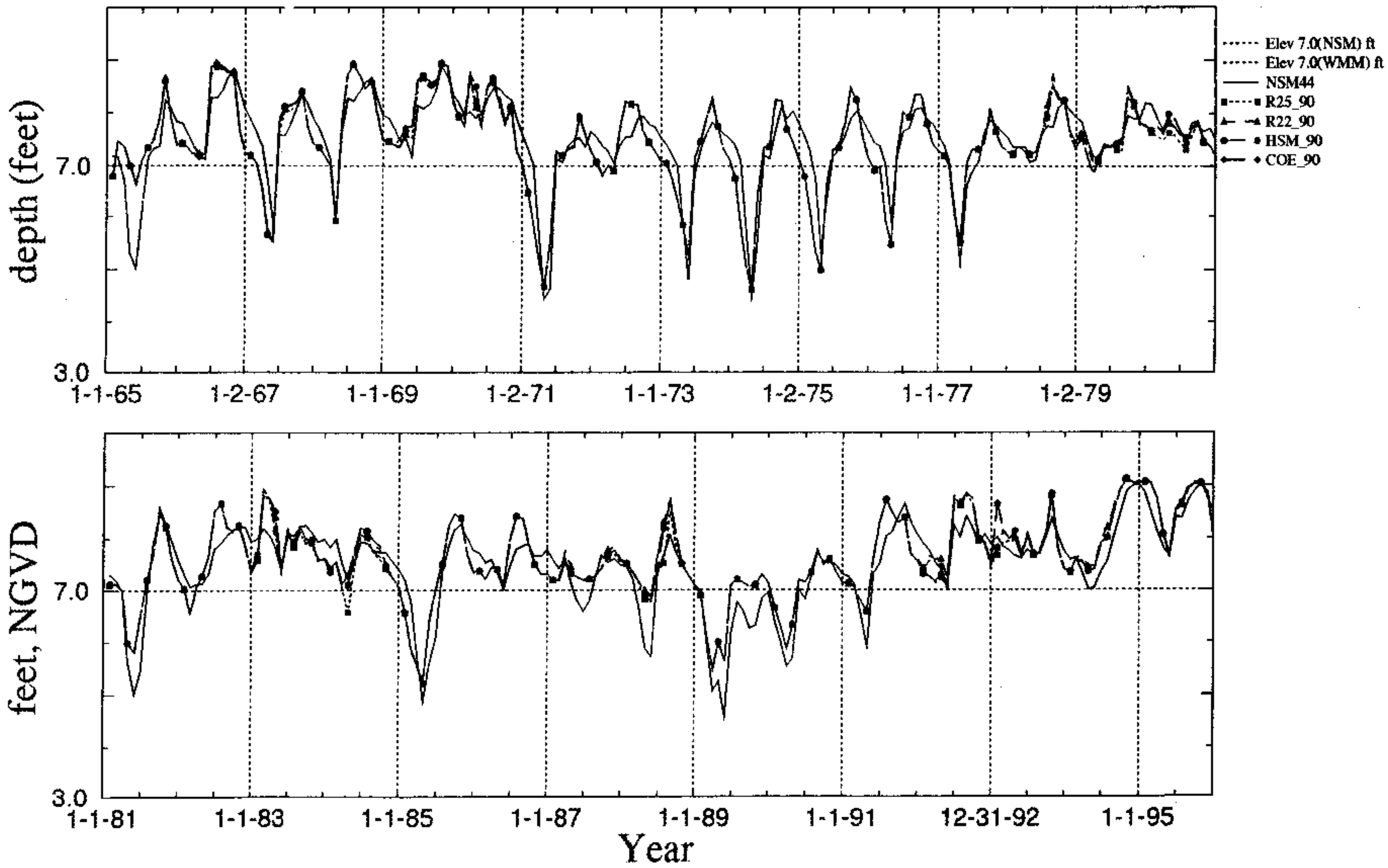
Environmental/ale/WCA/ENP
SFWMM Simulation

Stage Duration Curves for Marl Lands in NW SRS
Gage G-620, ENP, Cell R19 C18



C-46

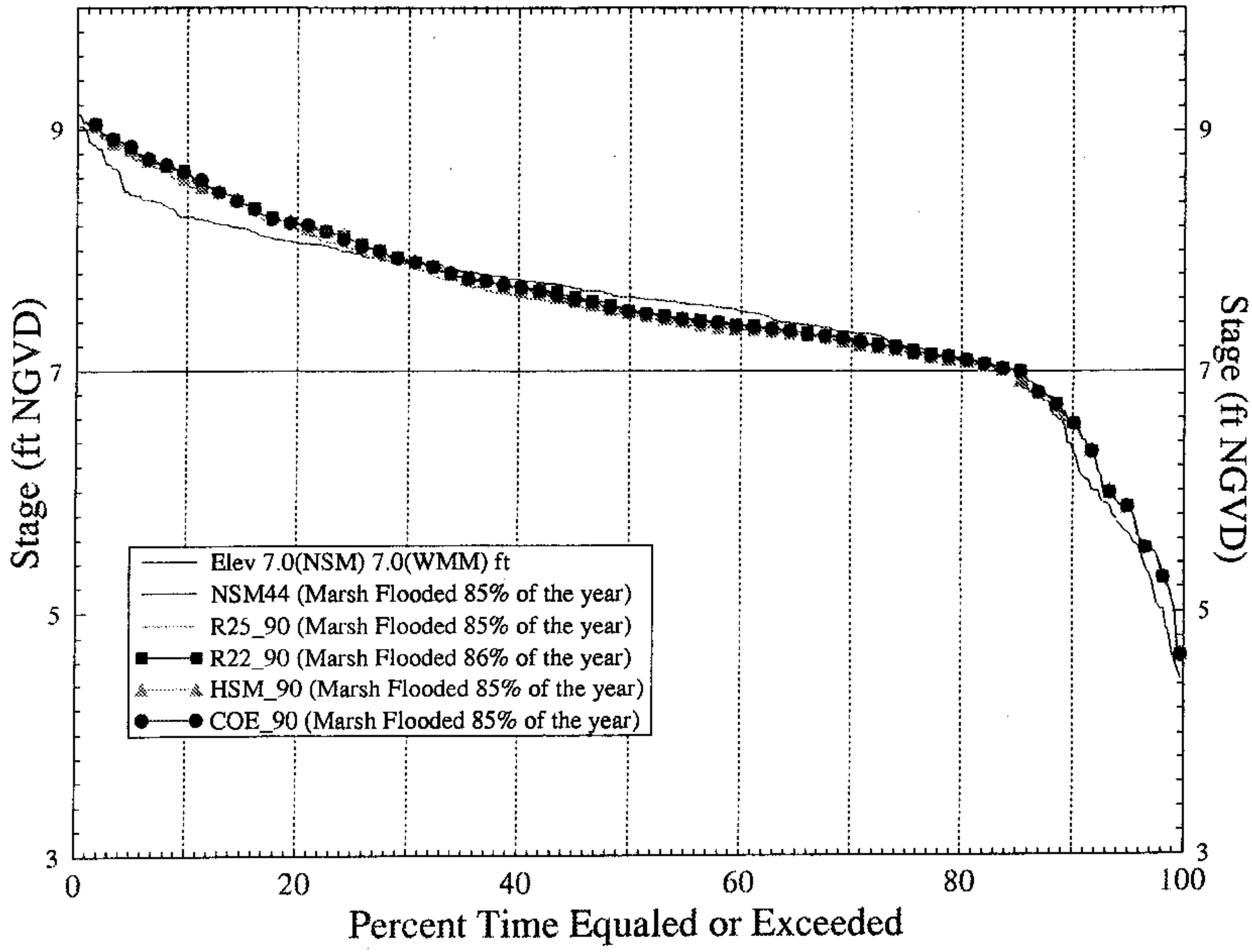
Stage Hydrograph at Northern Shark River Slough
Gage NP-201, Cell R21 C19



Wed Apr 30 12:14:38 1997

Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at Northern Shark River Slough
Gage NP-201, Cell R21 C19

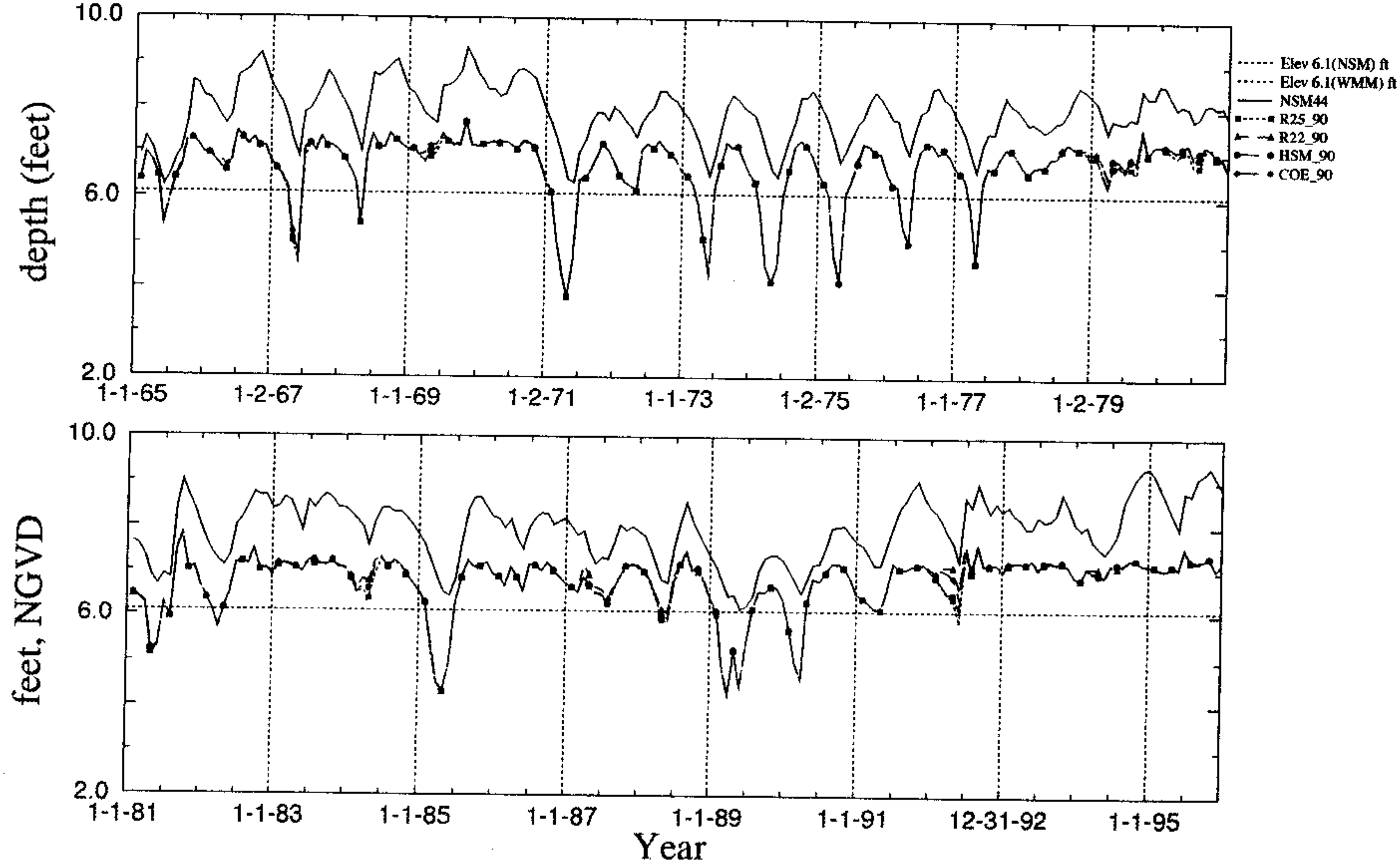


C-48

Wed Apr 30 12:11:38 1997

Environmental, Level II, ENP
SFWMM Simulation

Stage Hydrograph at N.E. Shark River Slough
Gage NESRS-2, Cell R21 C24

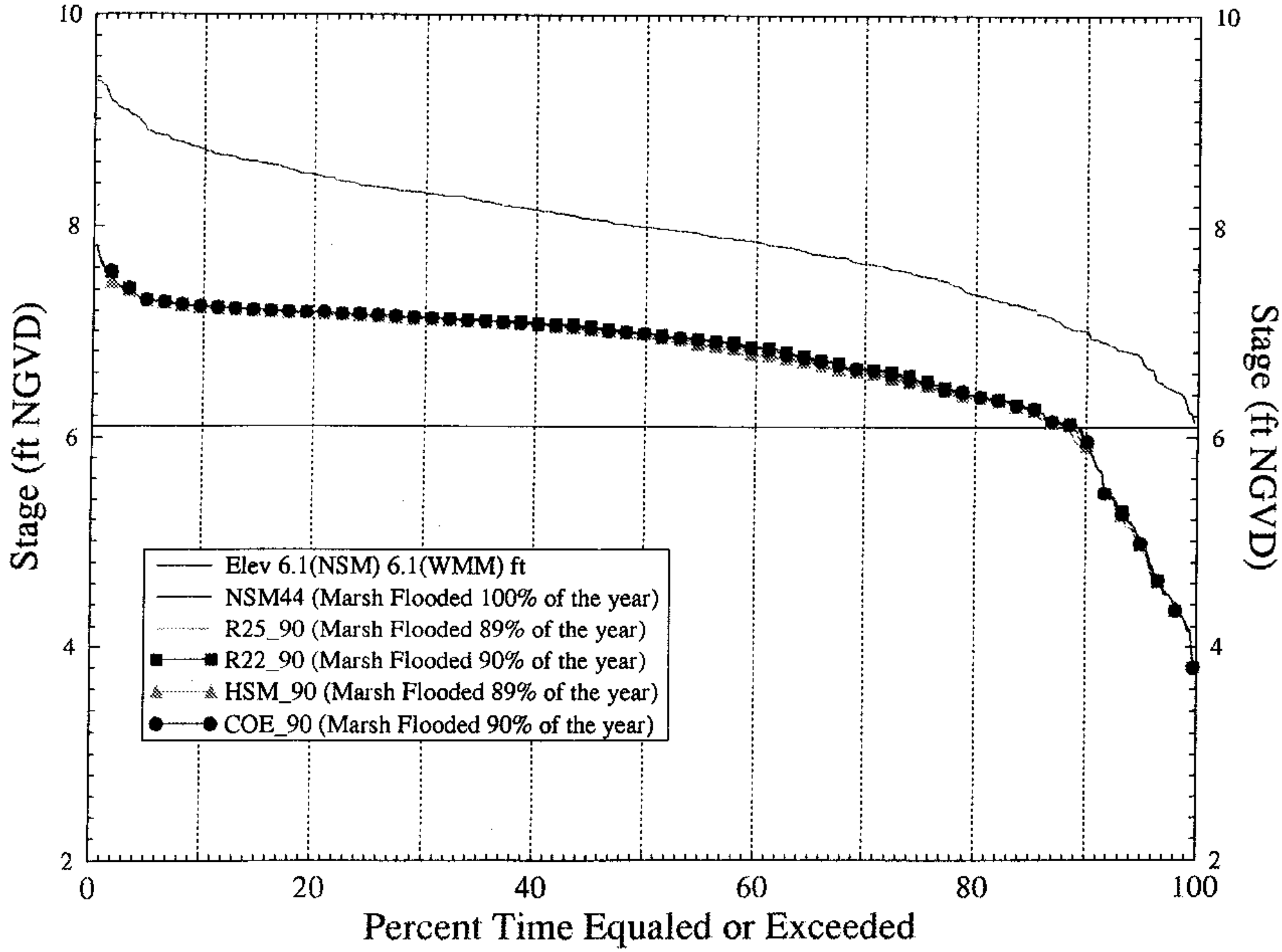


C-49

Wed Apr 30 12:14:24 1997

Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at N.E. Shark River Slough
Gage NESRS-2, Cell R21 C24

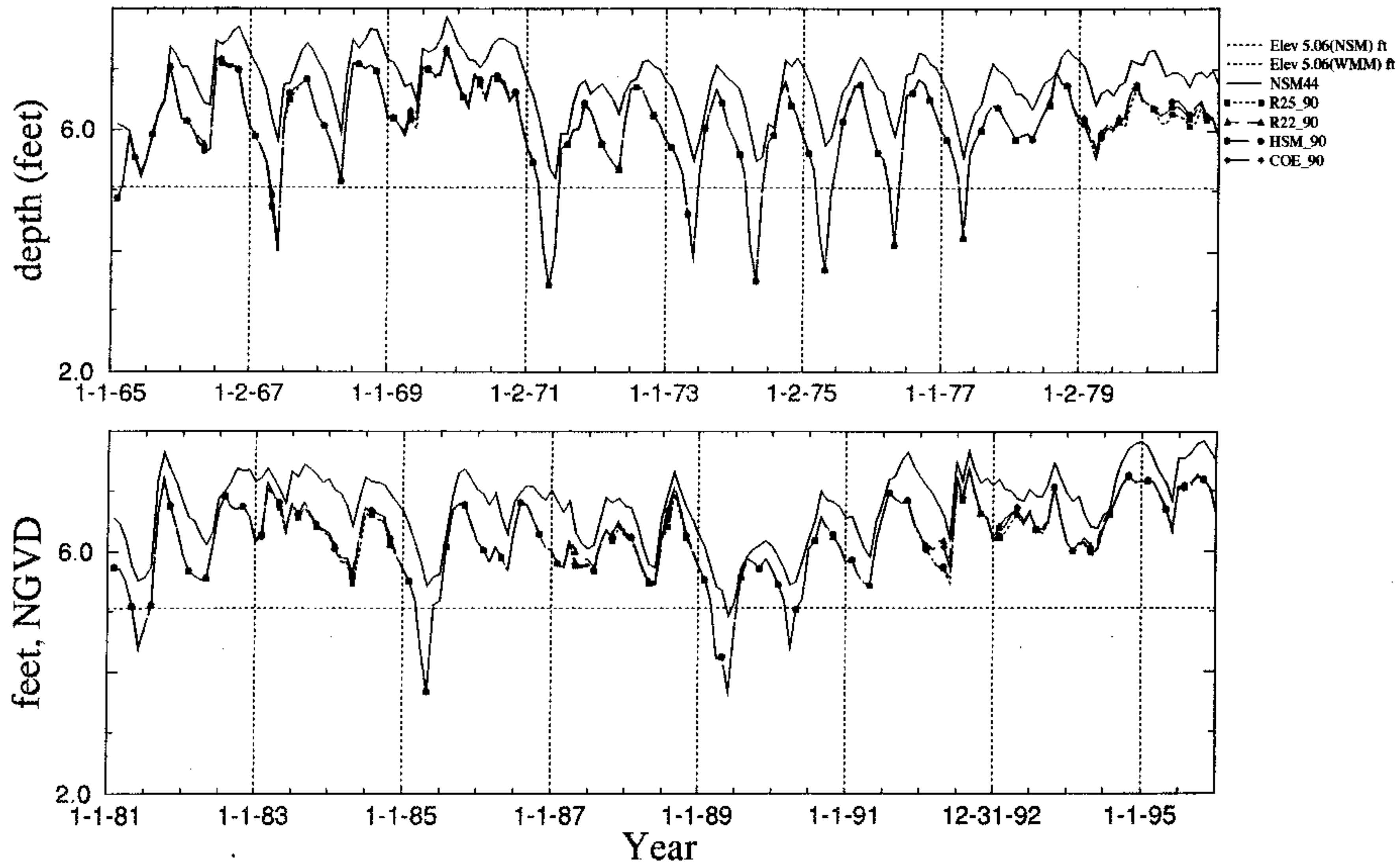


C-50

Wed Apr 30 12:11:19 1997

Environmental, Level II, ENP
SFWMM Simulation

Stage Hydrograph at Everglades National Park
Gage NP-33, Cell R17 C20

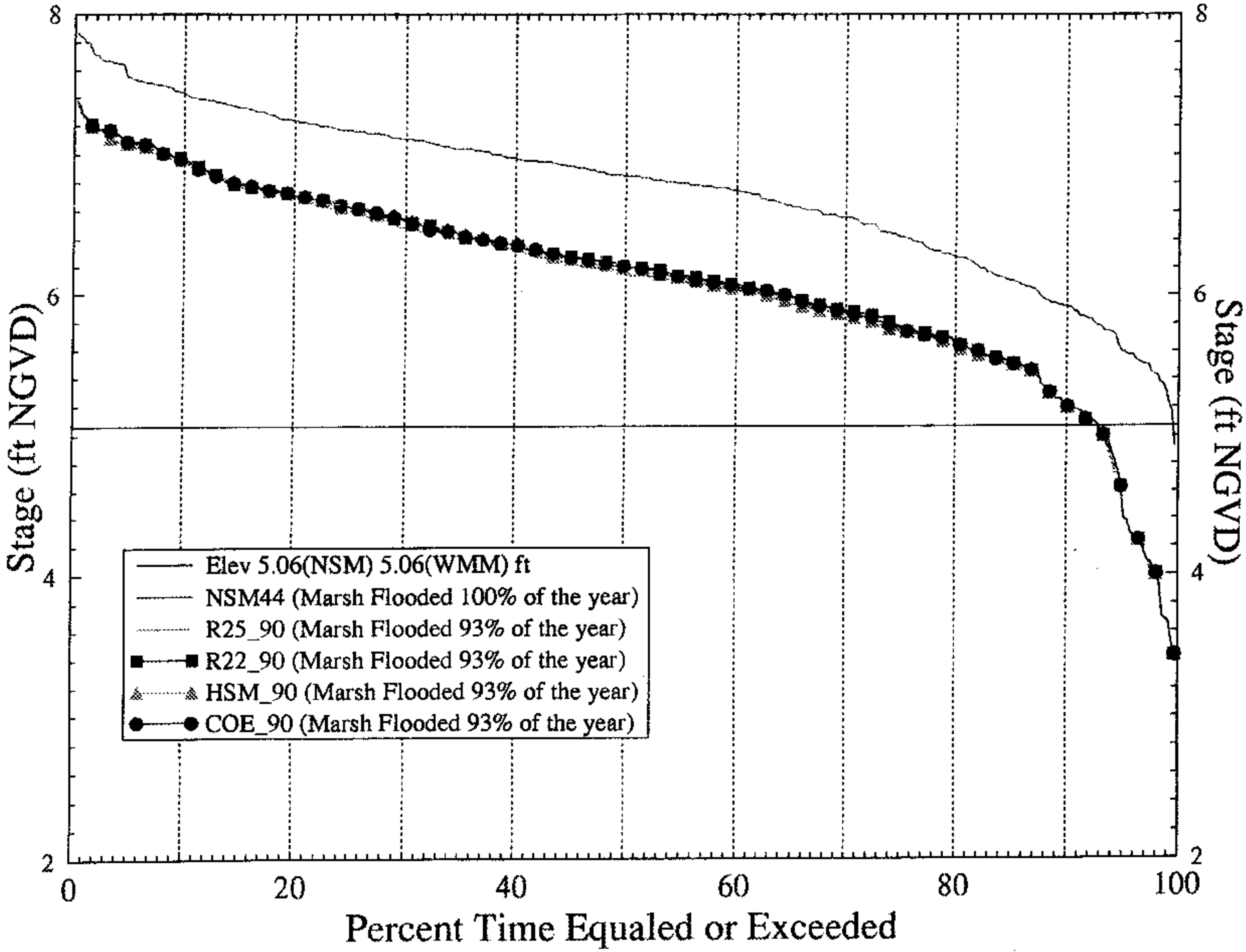


C-51

Wed Apr 30 12:14:51 1997

Environmental/WCA/ENP
SFWMM Simulation

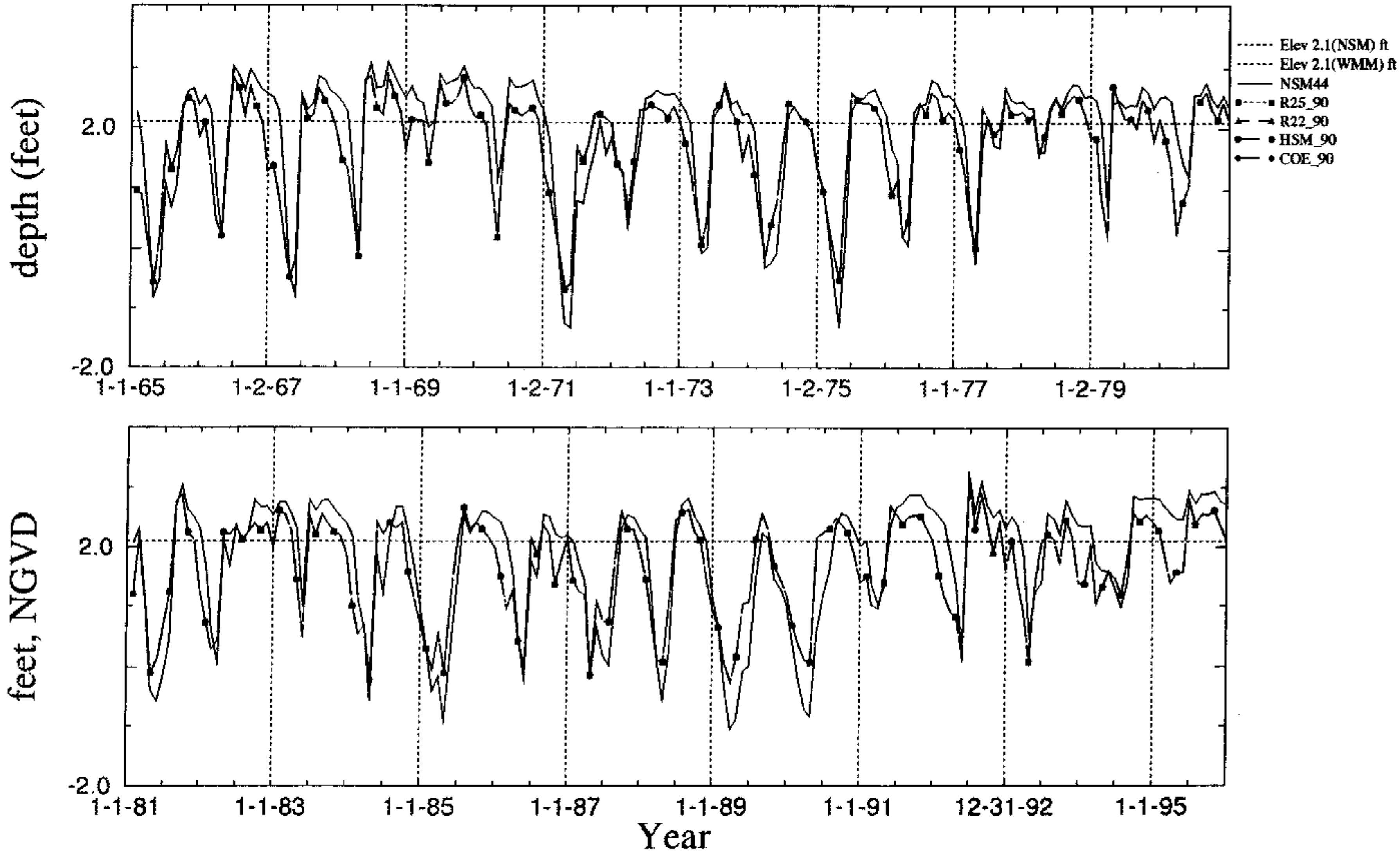
Stage Duration Curves at Everglades National Park
Gage NP-33, Cell R17 C20



Wed Apr 30 12:11:53 1997

Environmental, Level II, ENP
SFWMM Simulation

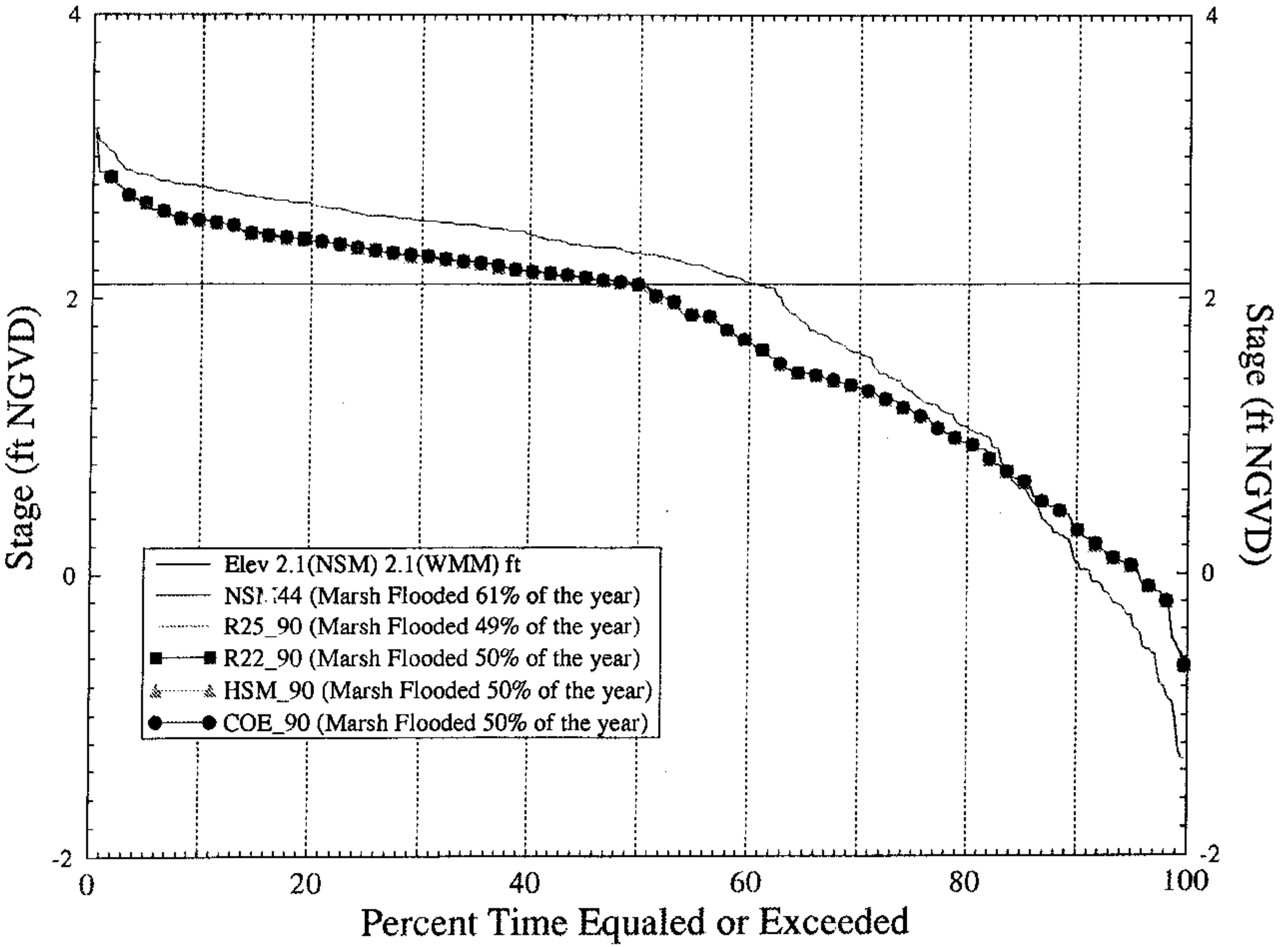
Stage Hydrograph at C-111 Basin
Gage G-1251, Cell R7 C24



Wed Apr 30 12:13:58 1997

Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at C-111 Basin
Gage G-1251, Cell R7 C24

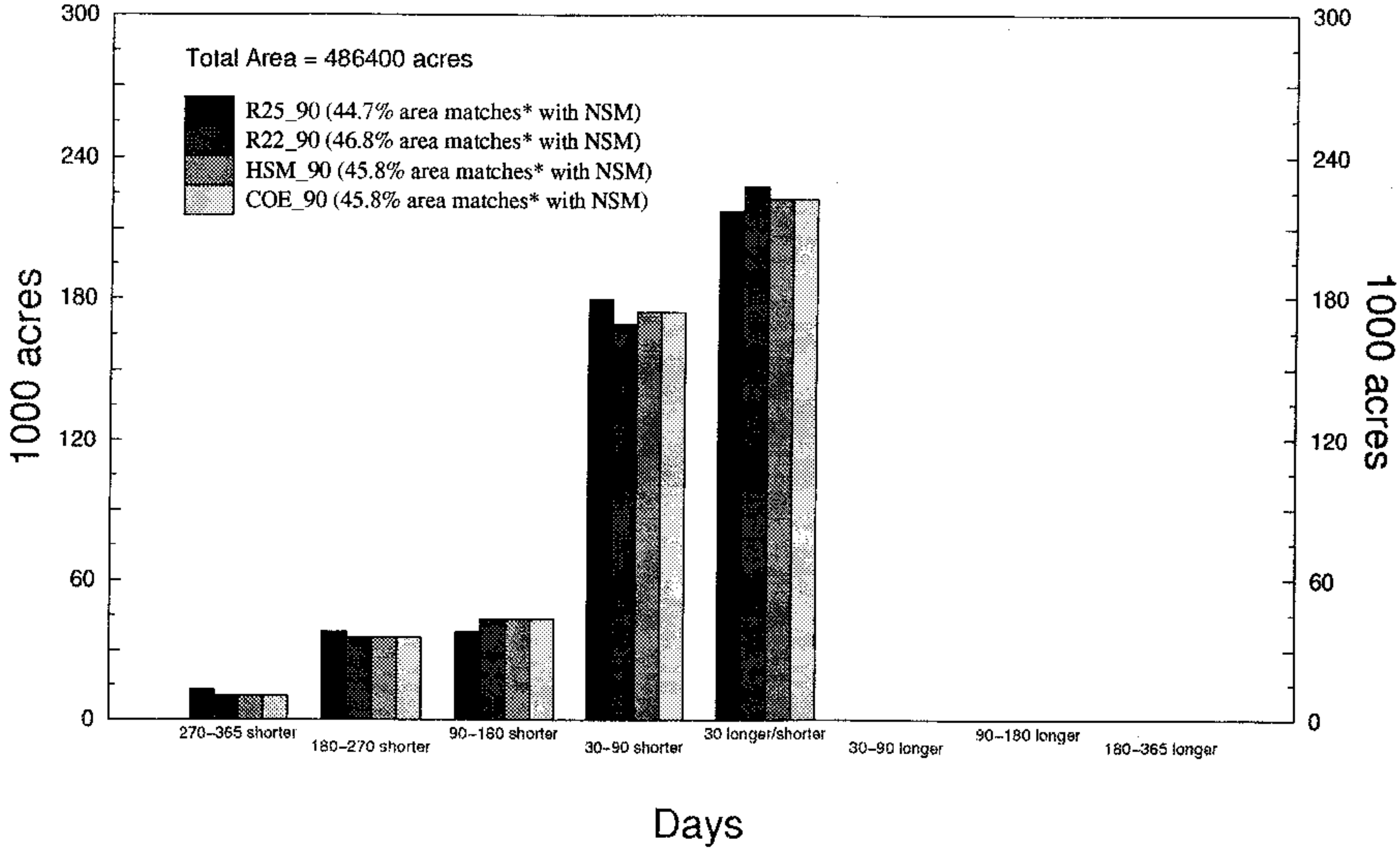


Wed Apr 30 12:13:29 1997

Environmental, Level II, ENP
SFWMM Simulation

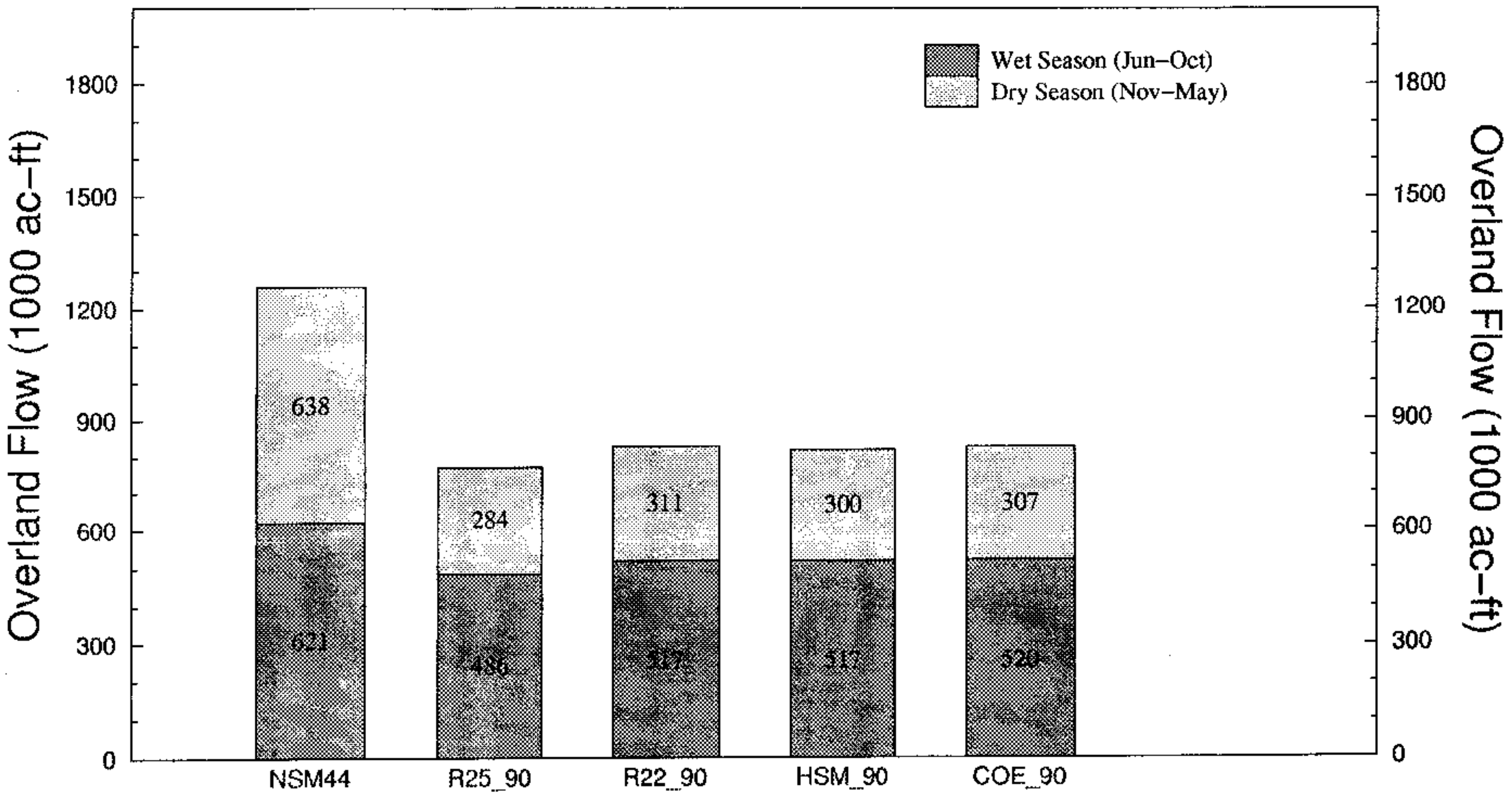
C-54

Mean NSM hydroperiod matches for the Everglades National Park for the 31 yr. simulation



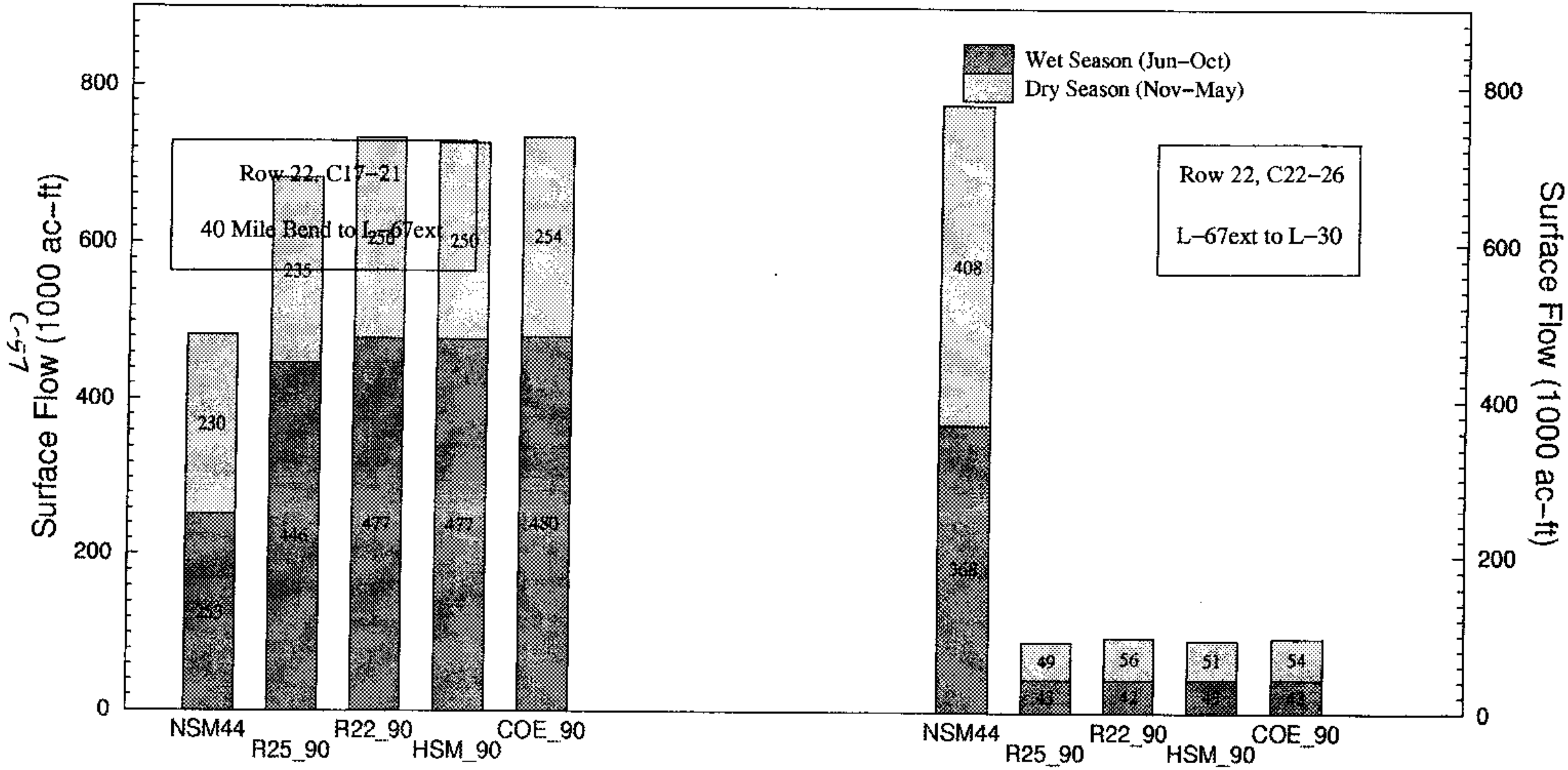
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wet/Dry Season Average Overland Flows South of Tamiami Trail to ENP for the 31 yr. simulation



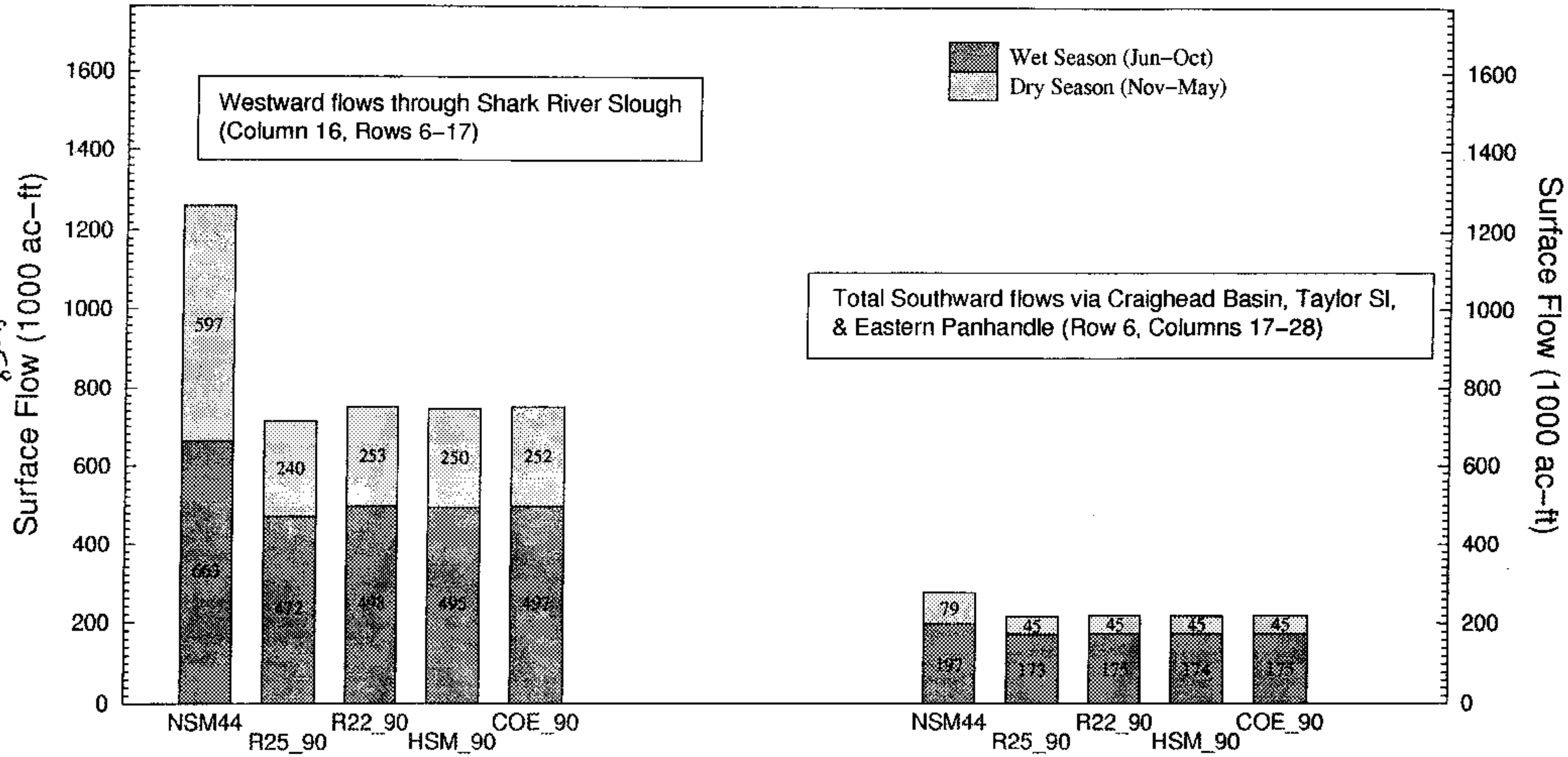
Note: Flow represents overland flows for cells Row 22 Columns 17 thru 26. NSM water depths at key ENP gage locations are used as operational

Average Annual Overland Flows to ENP South of Tamiami Trail, West & East of L-67ext for the 31 year simulation period



Note: Flow represents overland flows for cells Row 22 Columns 22 thru 26. NSM water depths at key ENP gage locations are used as operational targets for most alternatives. NSM flows are NOT targets (except for ALT #4) and are shown for comparative purposes only.

Average Annual Overland Flows toward Whitewater Bay and Florida Bay for the 31 year simulation period

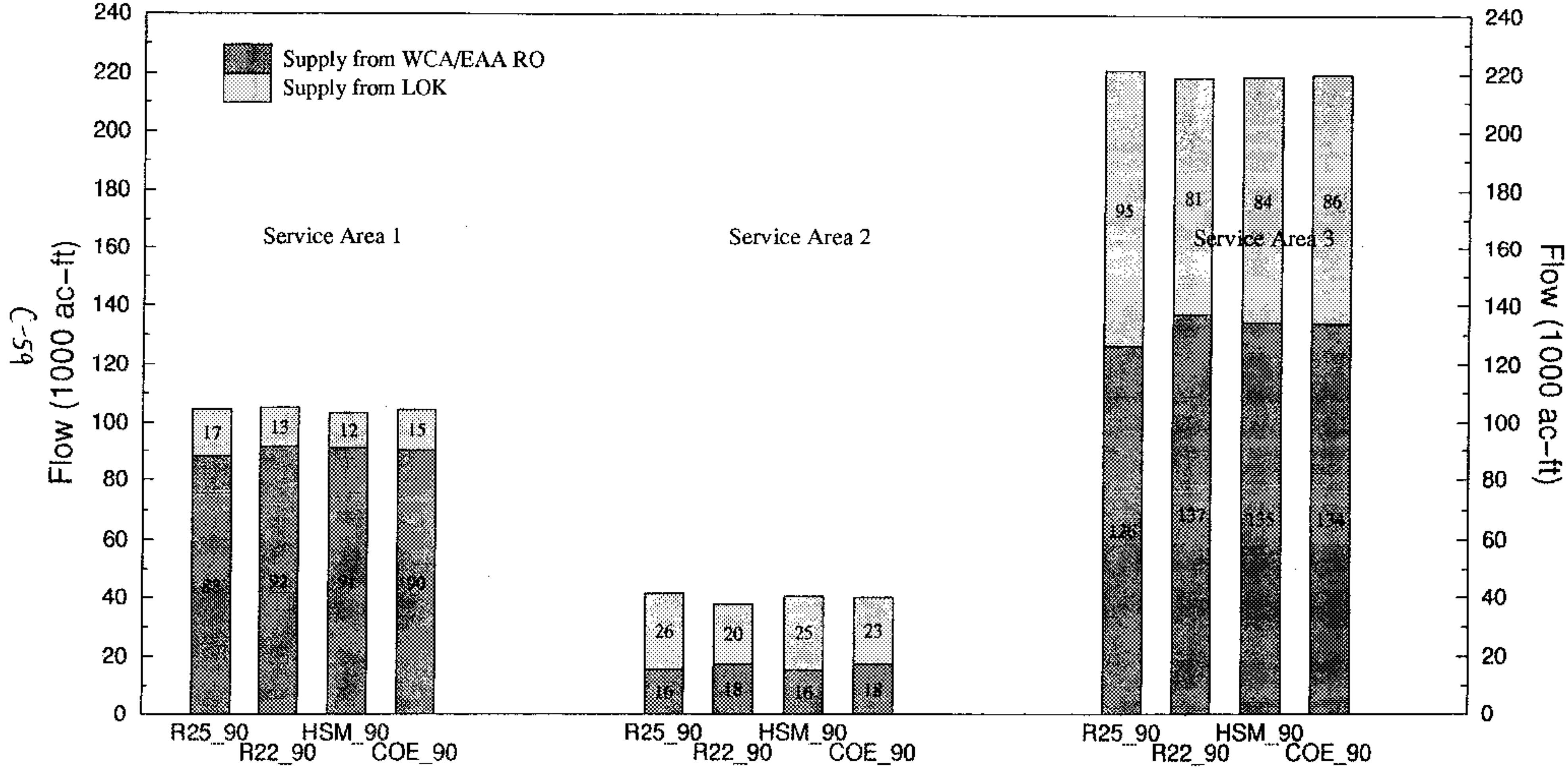


Note: NSM water depths at key ENP gage locations are used as operational targets for most alternatives.

Performance Measures for the

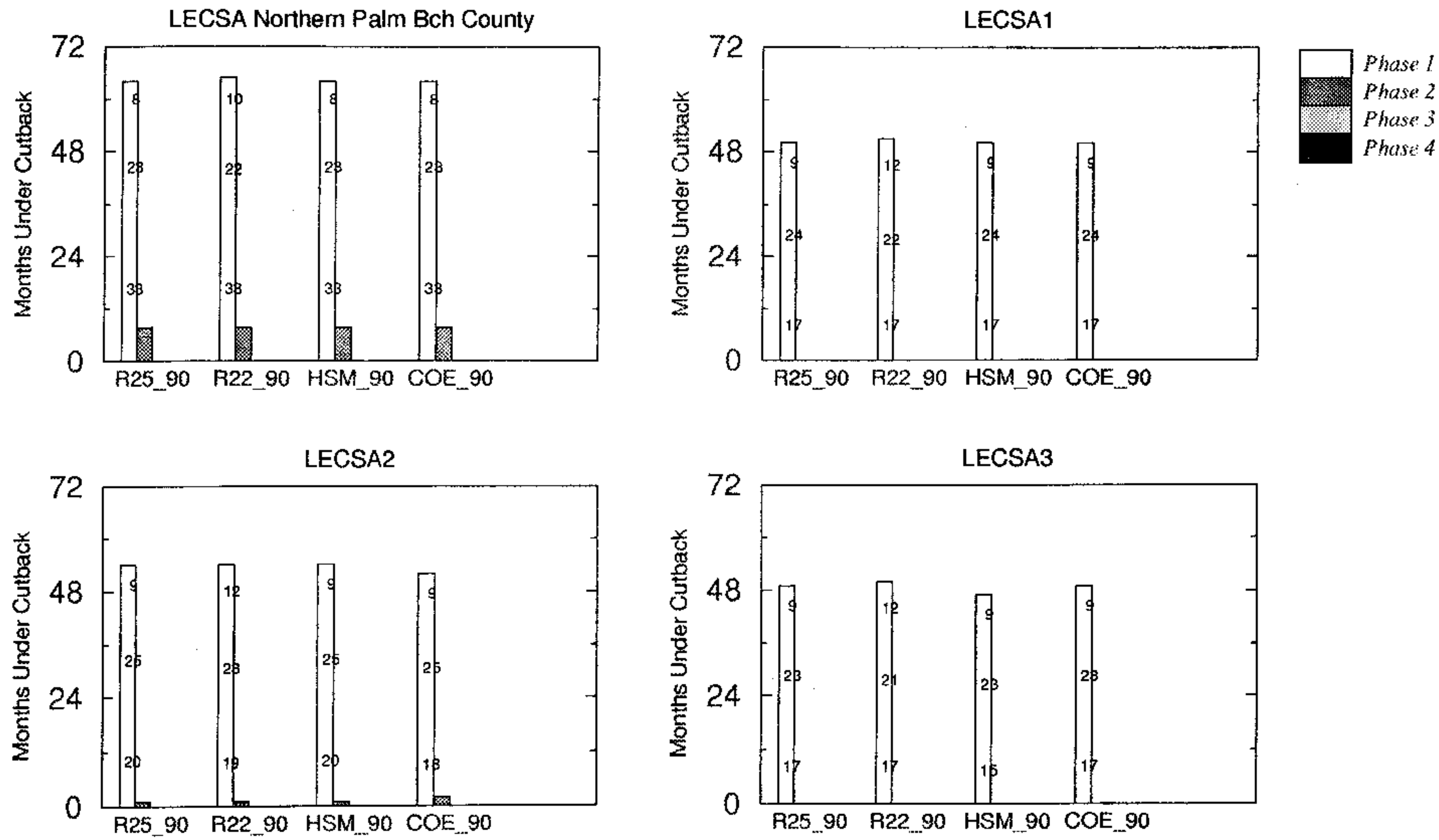
Lower East Coast Service Areas

Mean Annual Regional System Water Supply Deliveries to LEC Service Areas for the five Drought years (71,75,81,85,89)



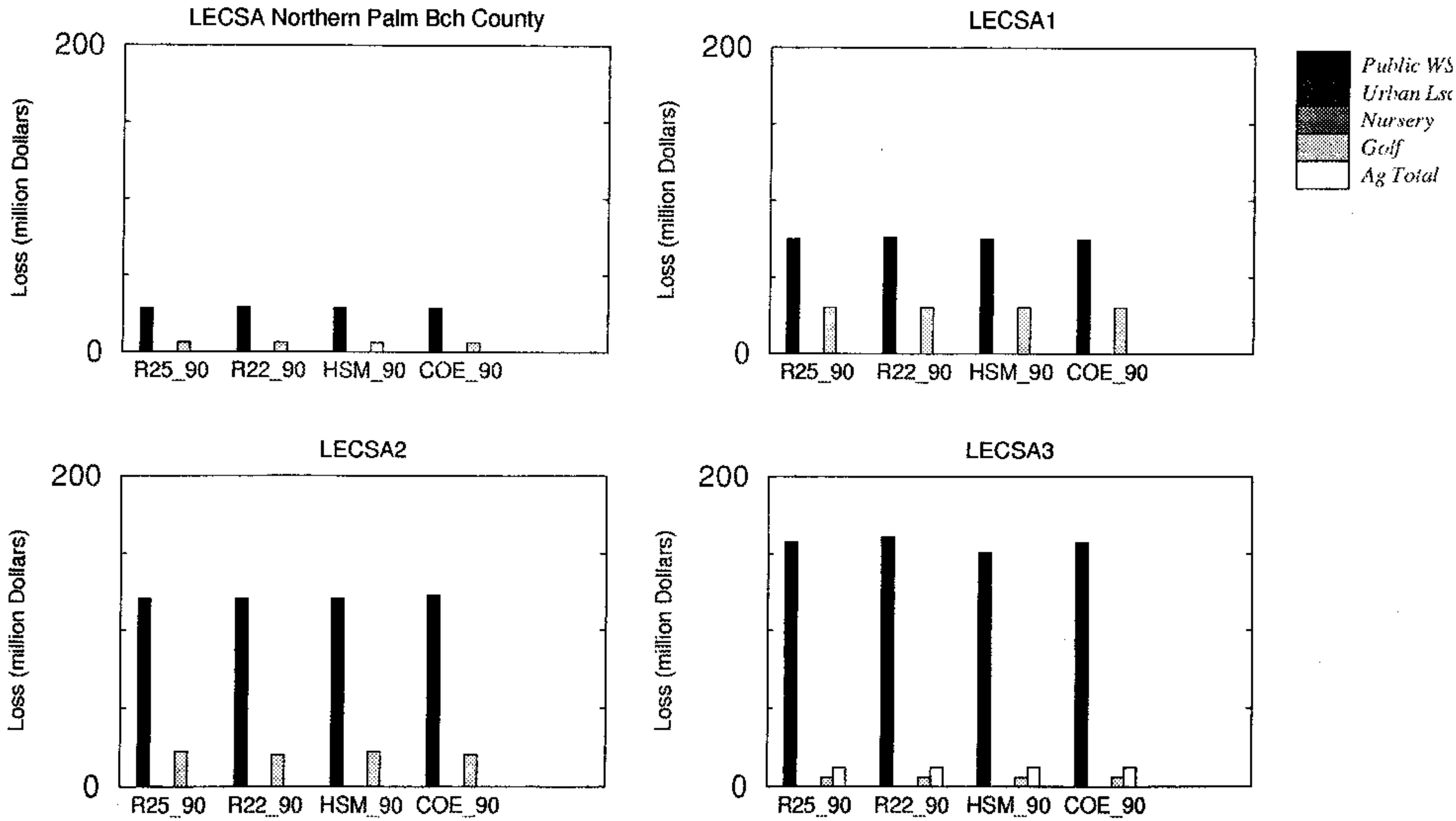
Note: Structure flows included: SA1=S39+LWDD+ADDSLW+ACMEWS+WSL8S; SA2=S38+S34; SA3=S31+S334+S337
Supply RECEIVED from LOK may be less than what is DELIVERED at LOK due to conveyance constraints.

Number of Months of Simulated Water Supply Cutbacks
for the 1965 – 1995 Simulation Period



Note: Phase 1 water restrictions could be induced by a) Lake stage in Supply Side Management Zone (indicated by upper data label), b) Local Trigger well stages (lower data label), and c) Dry season criteria (indicated by middle data label).

Total Water Shortage Impacts (Losses) for the 26 year Simulation Period

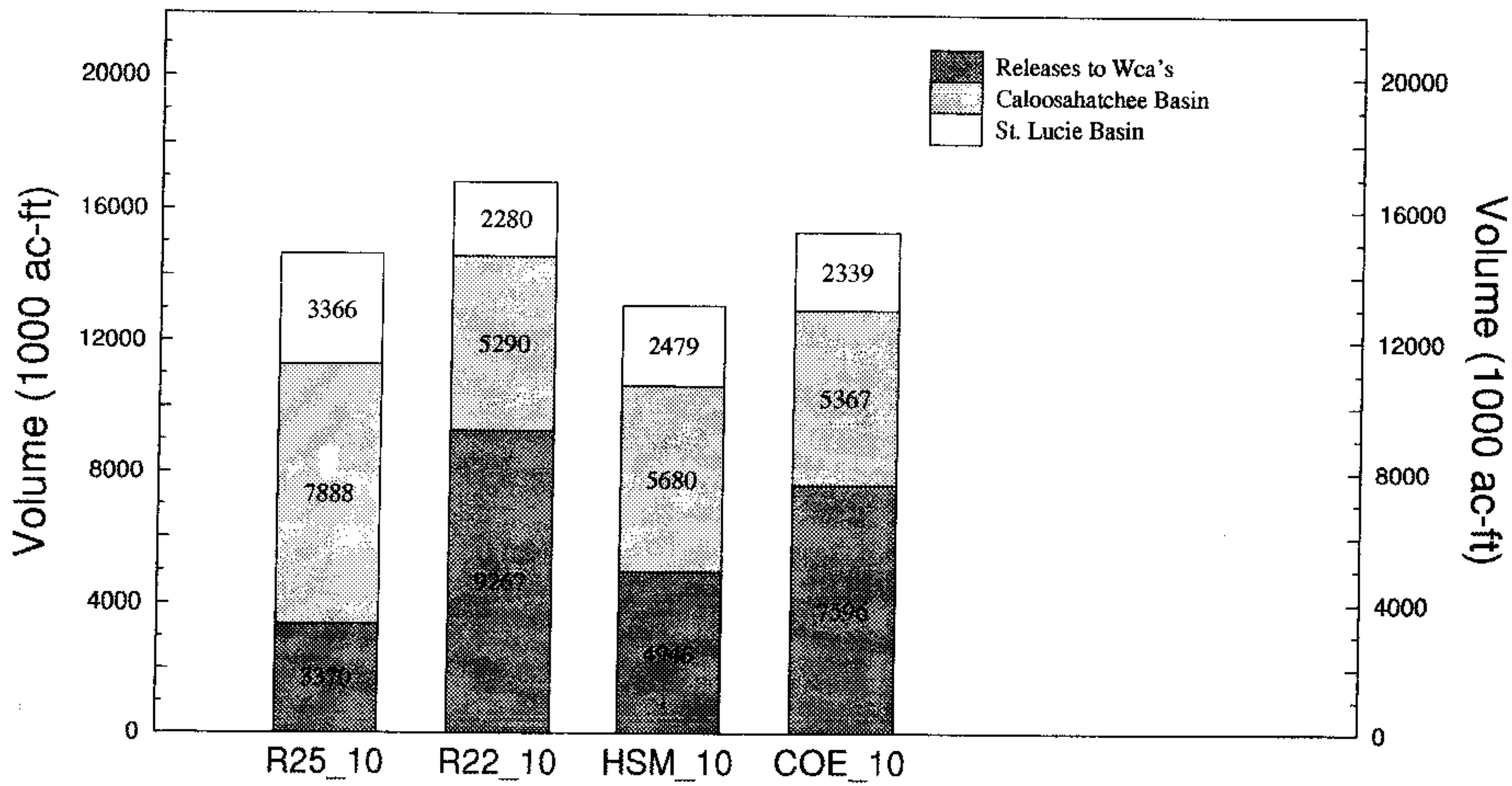


C-61

APPENDIX D. 2010 Simulations - Performance Measure Graphics

Performance Measures for
Lake Okeechobee

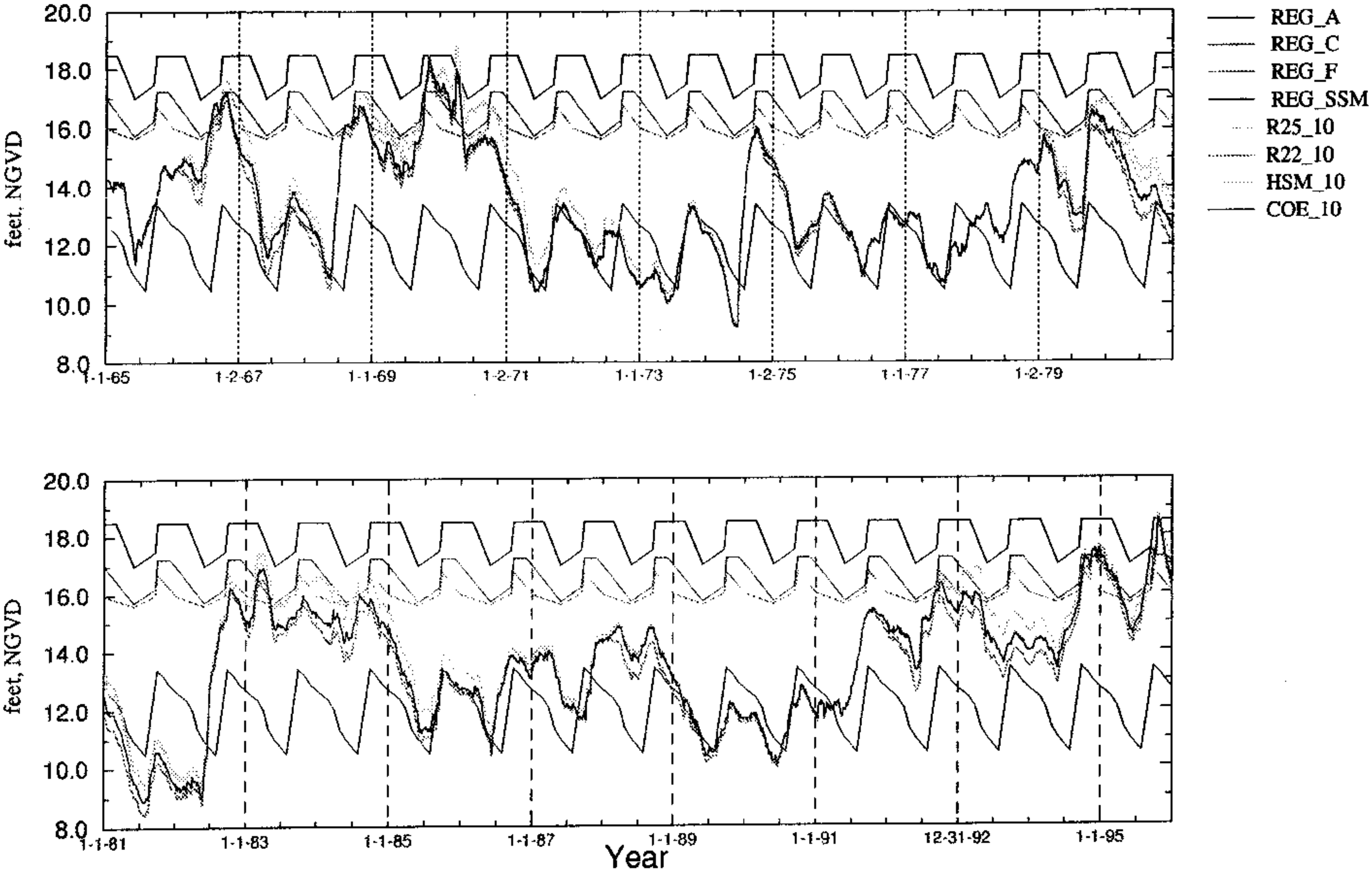
Total Flood Control Releases from Lake Okeechobee for the 31 yr (1965 - 1995) Simulation



Wed Apr 30 14:06:18 1997

Environmental, LOK
SFWMM Simulation

Daily Stage Hydrographs for Lake Okeechobee

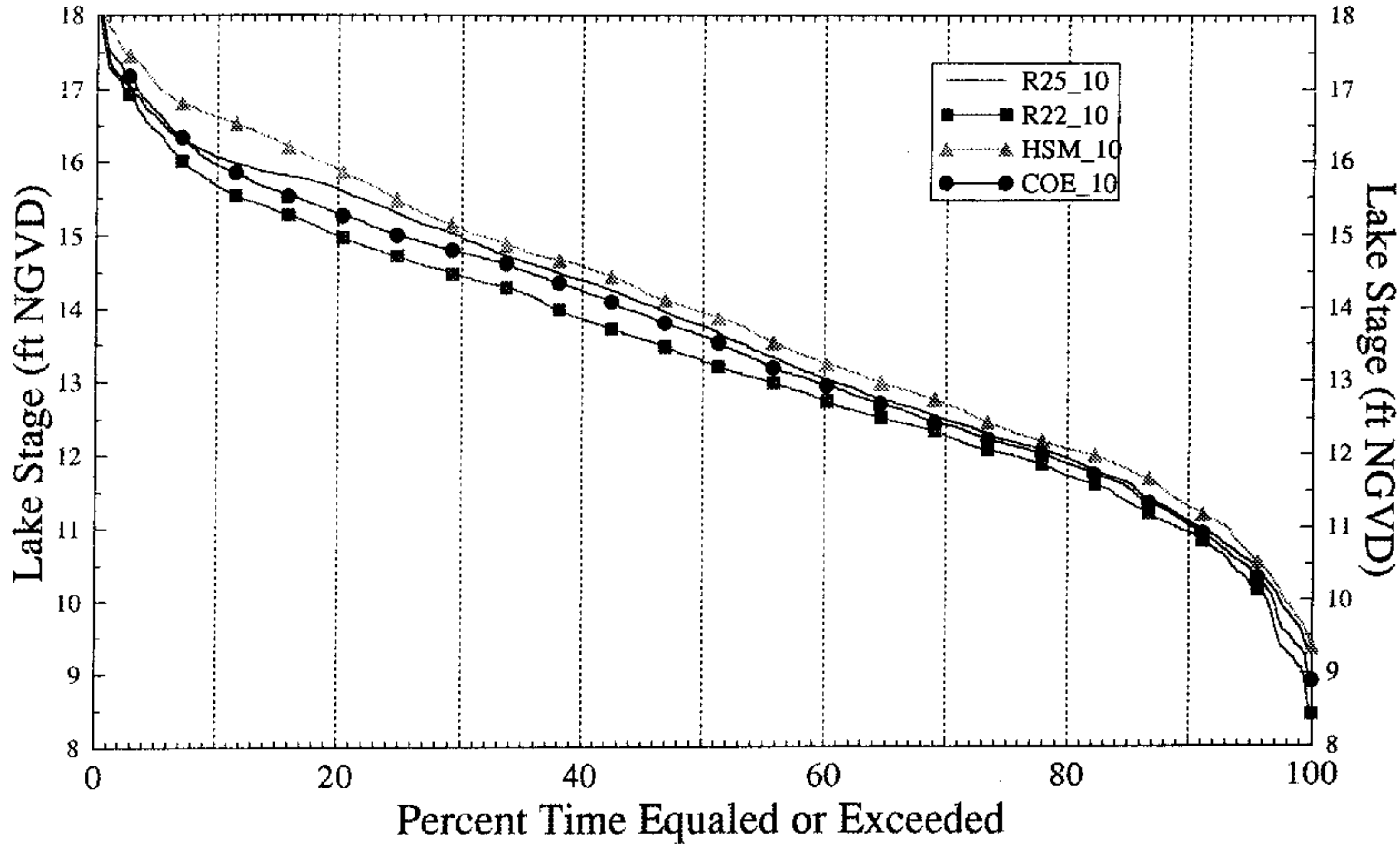


D-3

SFWMM Simulation

Wed Apr 30 14:17:56 1997

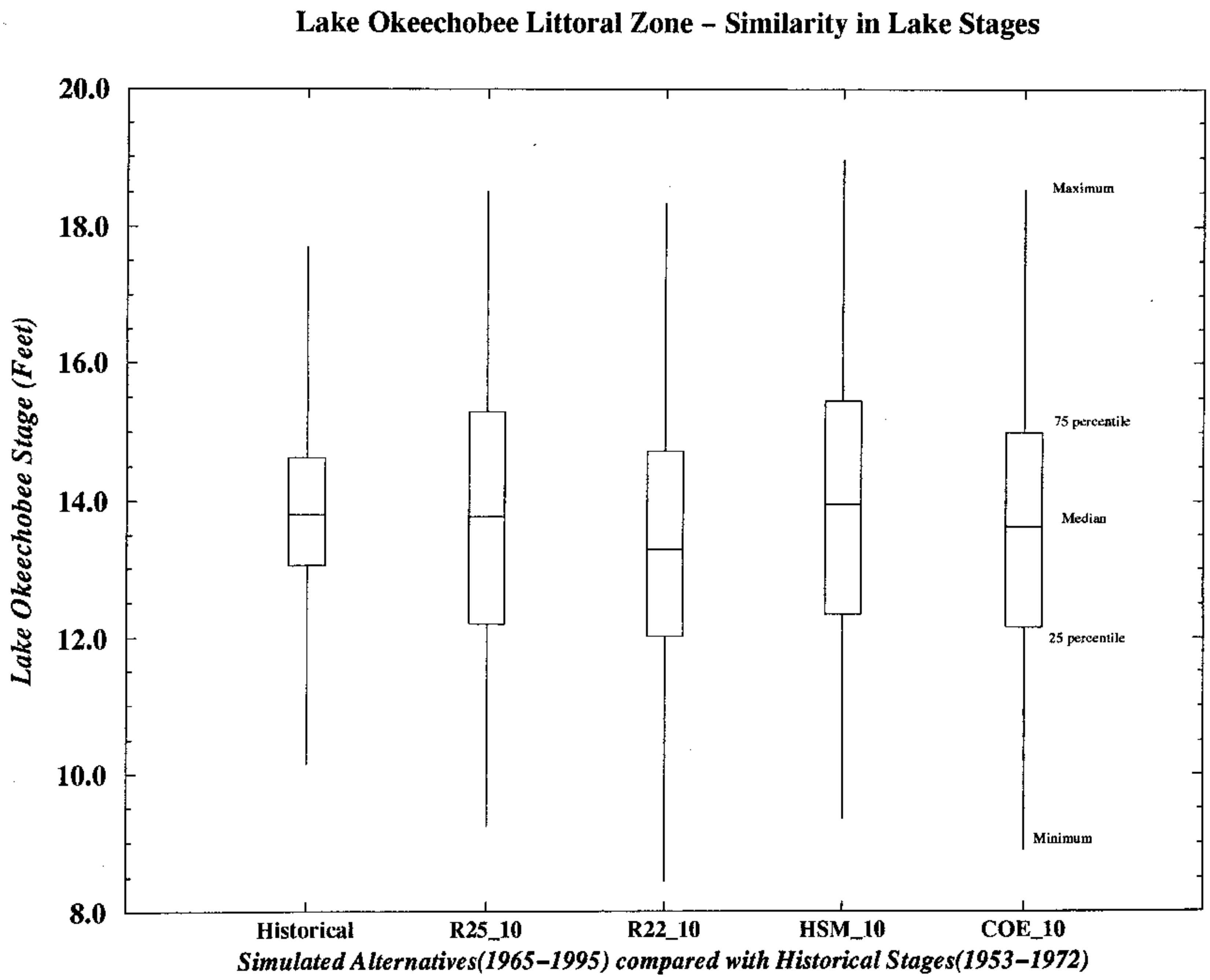
Lake Okeechobee Stage Duration Curves



h-4

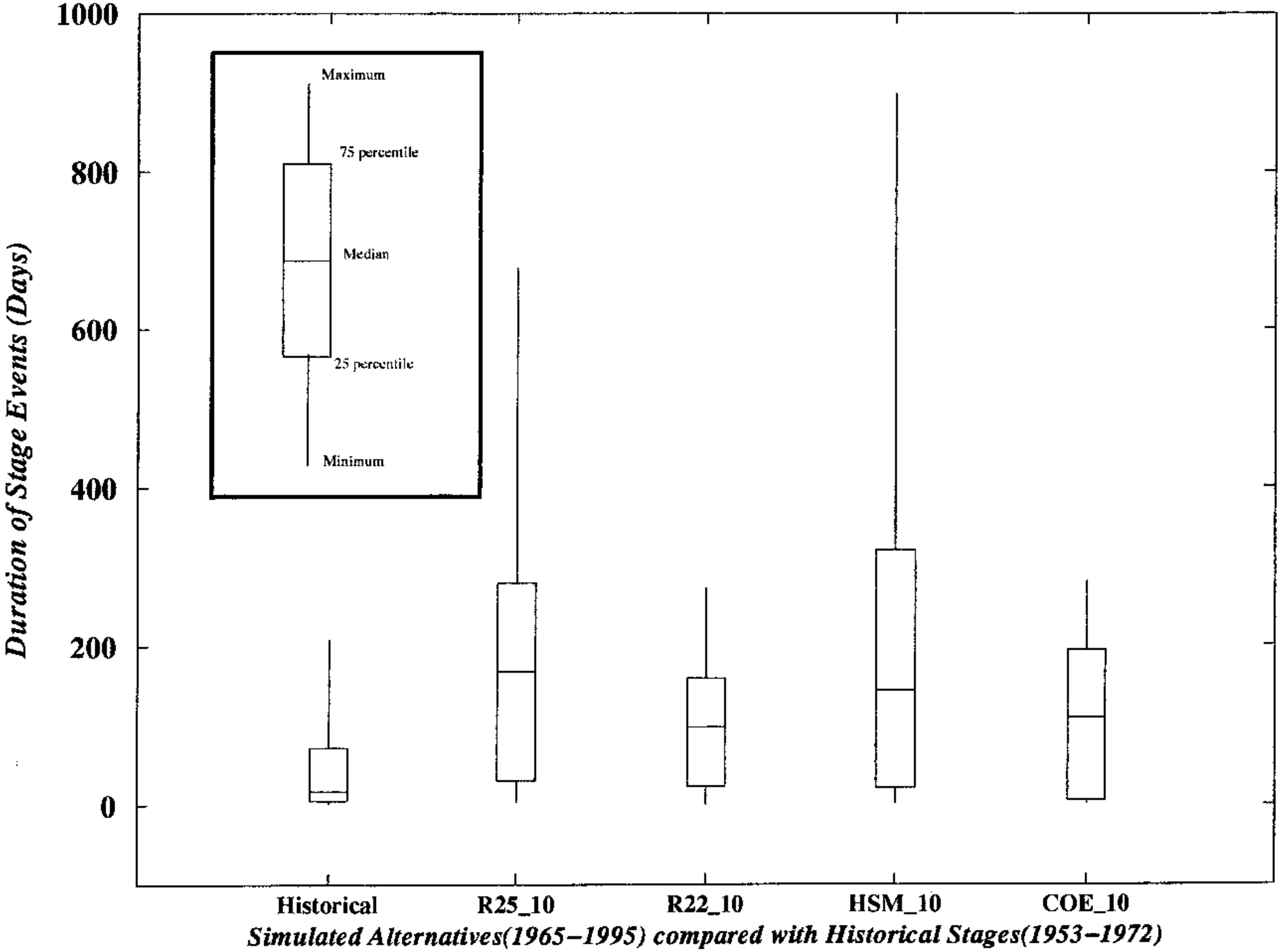
Wed Apr 30 14:07:07 1997

Environmental, Level I, LOK
SFWMM Simulation

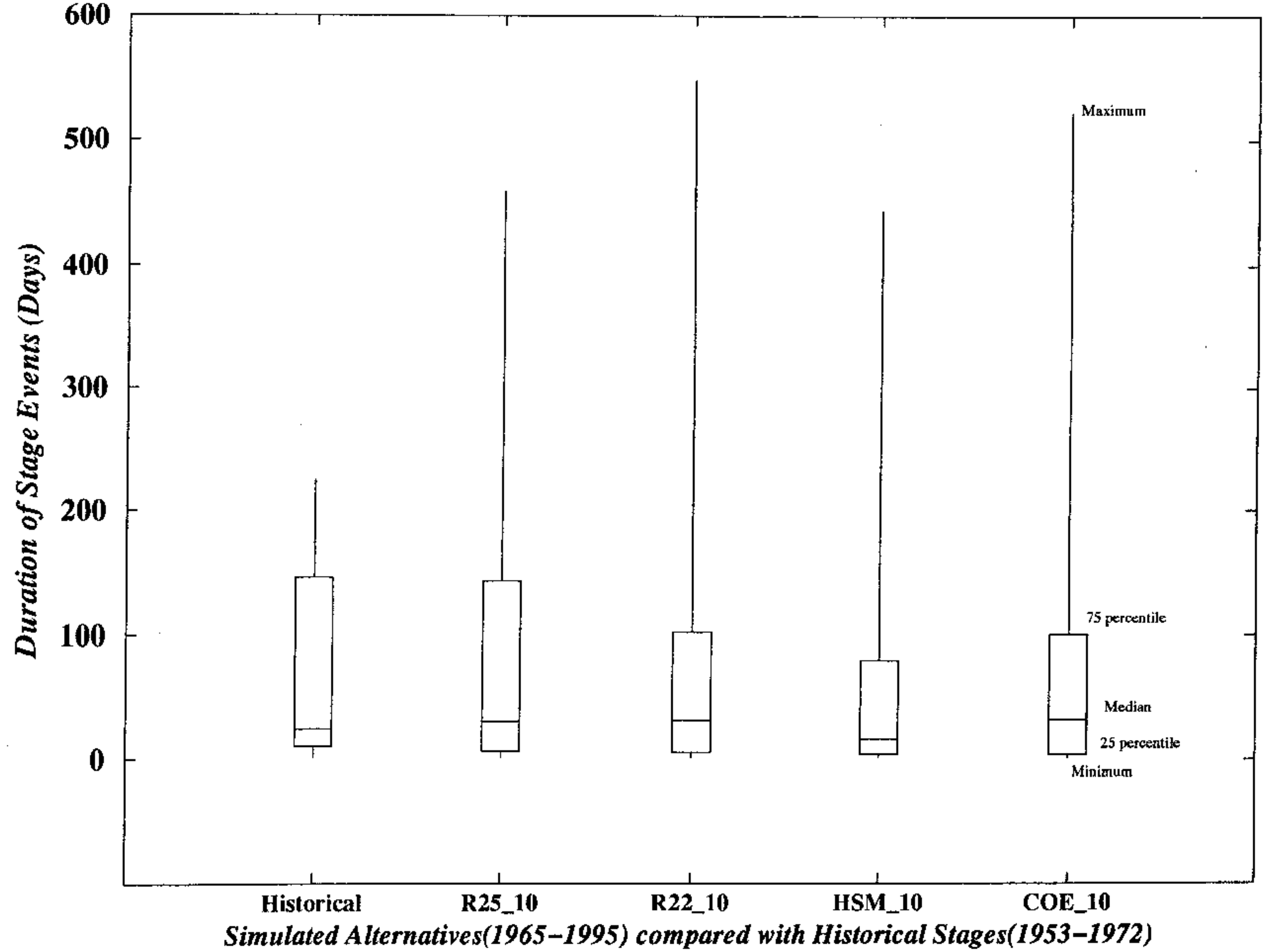


Lake Okeechobee Littoral Zone – Similarity in Lake Stages
Lake Okeechobee Stage (Feet)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
Maximum
75 percentile
Median
25 percentile
Minimum
Historical
R25_10
R22_10
HSM_10
COE_10
Simulated Alternatives(1965–1995) compared with Historical Stages(1953–1972)

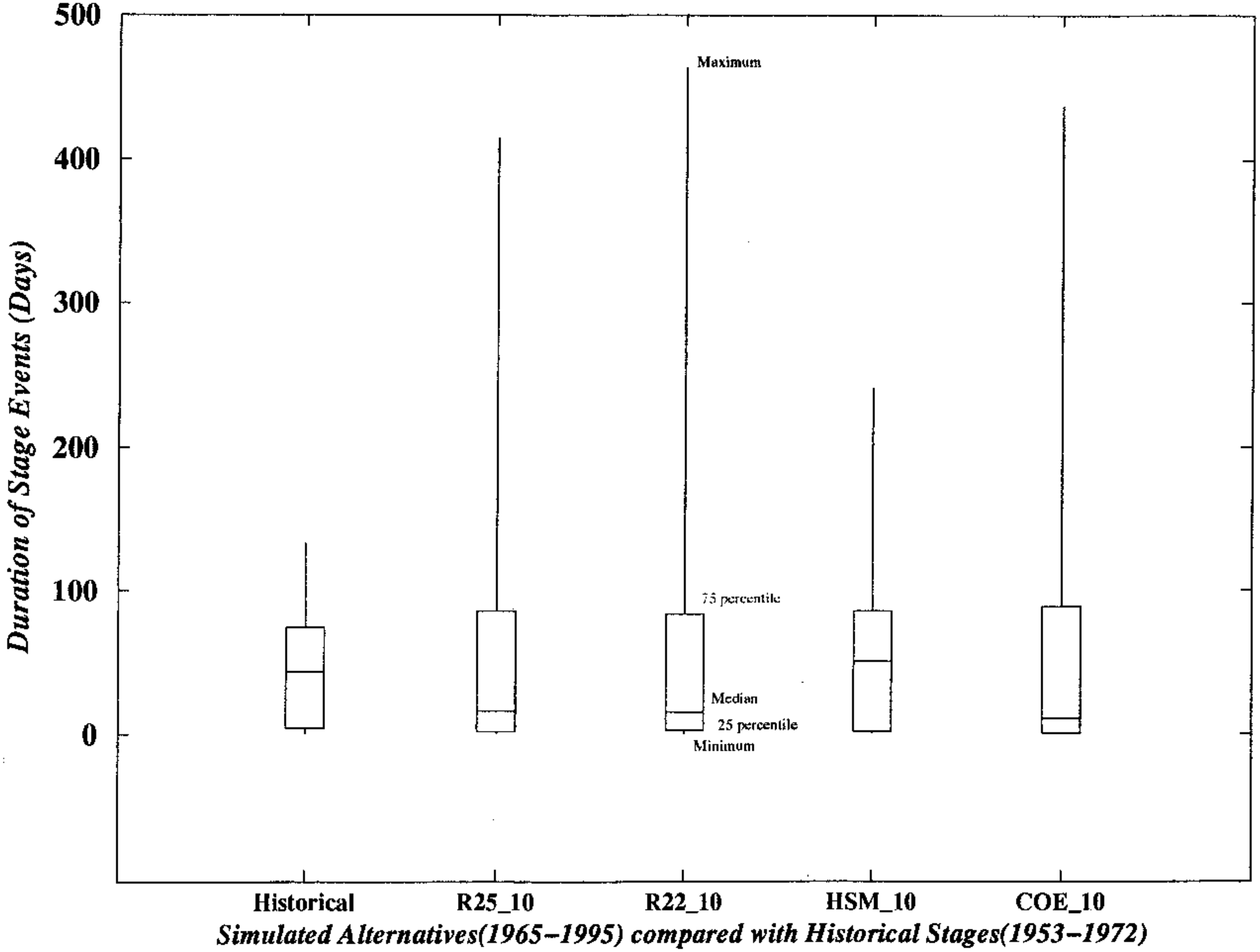
Lake Okeechobee Littoral Zone – Similarity in Duration of Stage Events > 15 feet



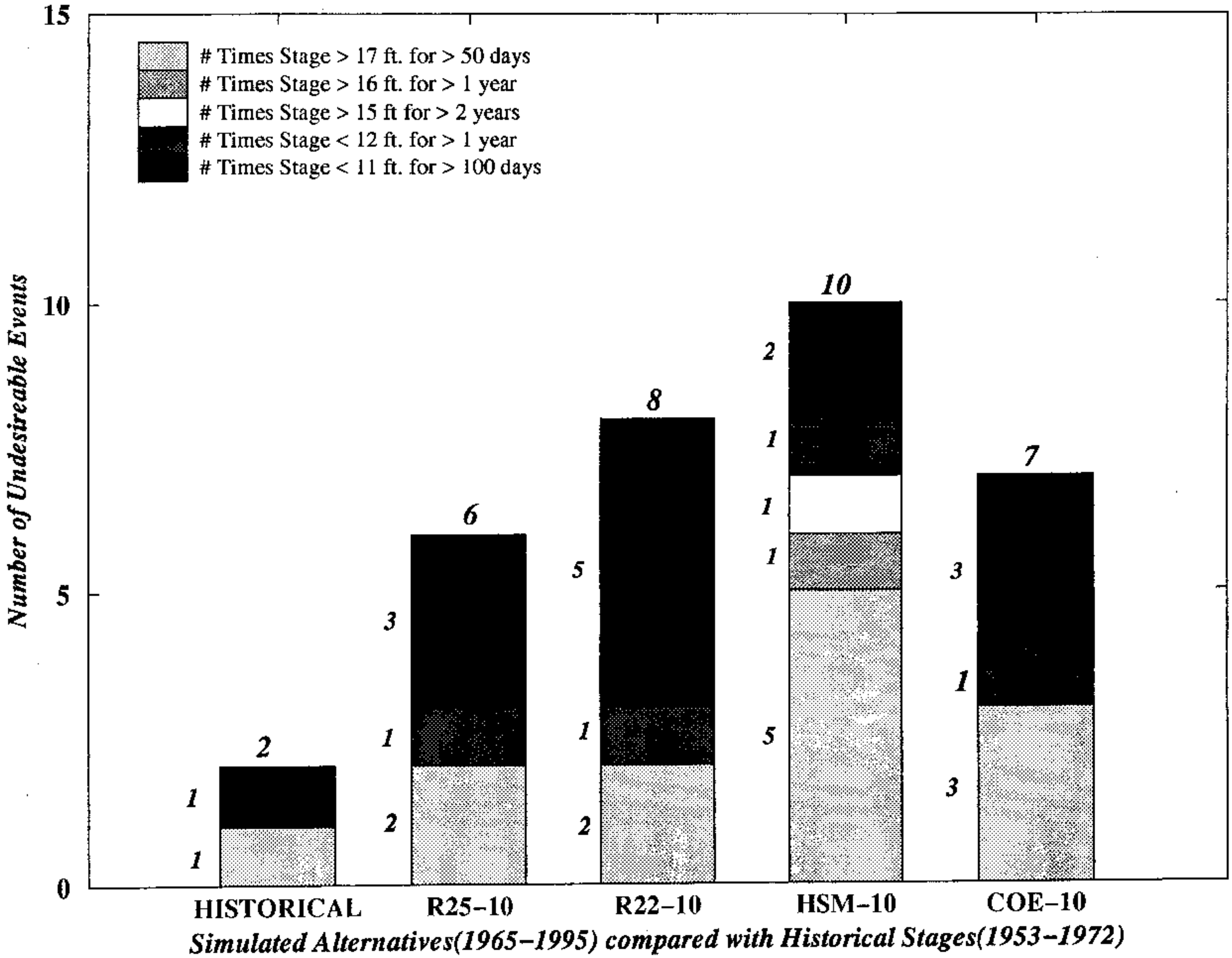
Lake Okeechobee Littoral Zone – Similarity in Duration Stages < 12 feet



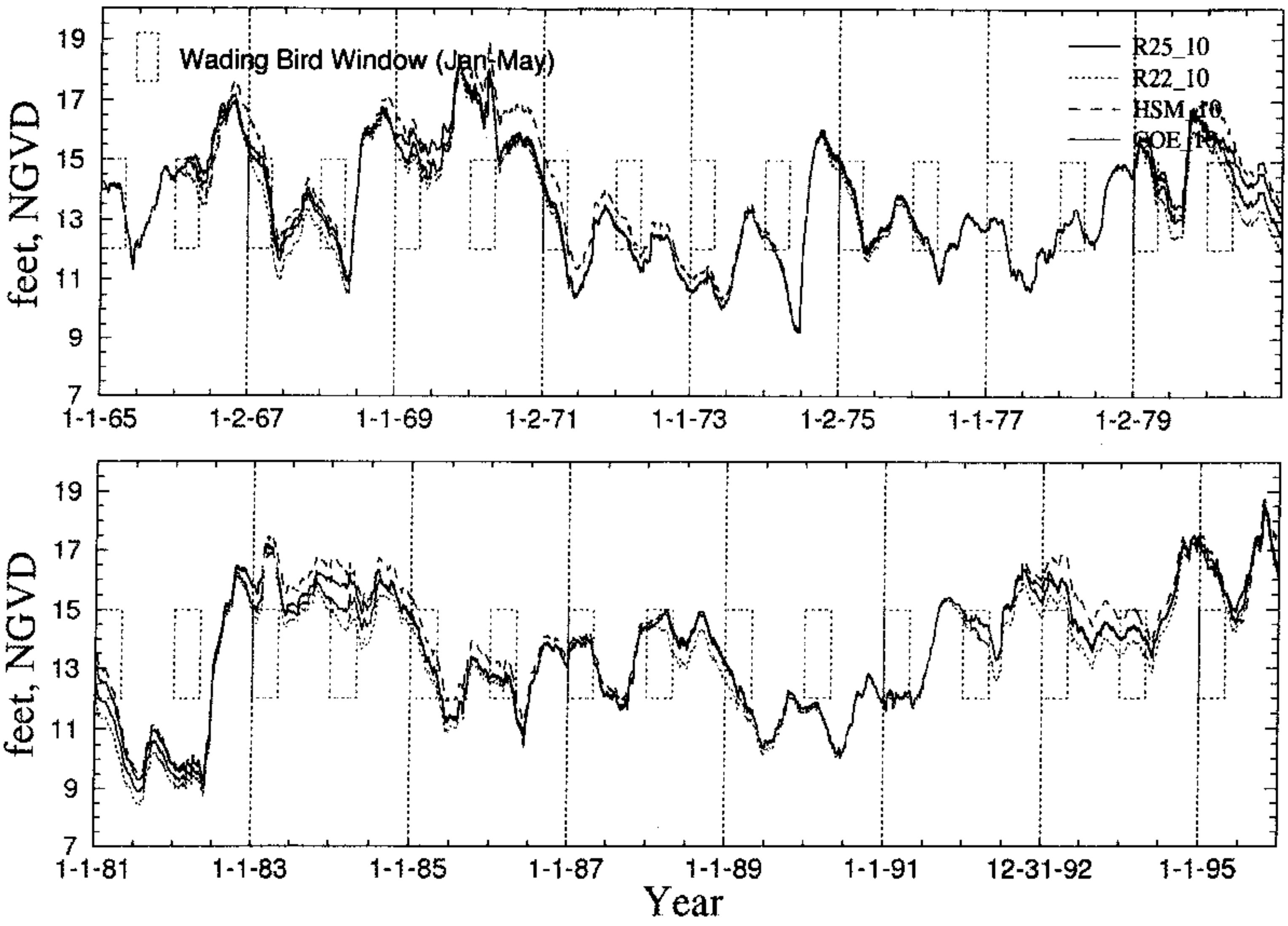
Lake Okeechobee Littoral Zone – Similarity in Duration of Stage Events < 11 feet



Number of Undesireable Lake Okeechobee Stage Events



Daily Stage Hydrographs for Lake Okeechobee
Wading Bird Windows



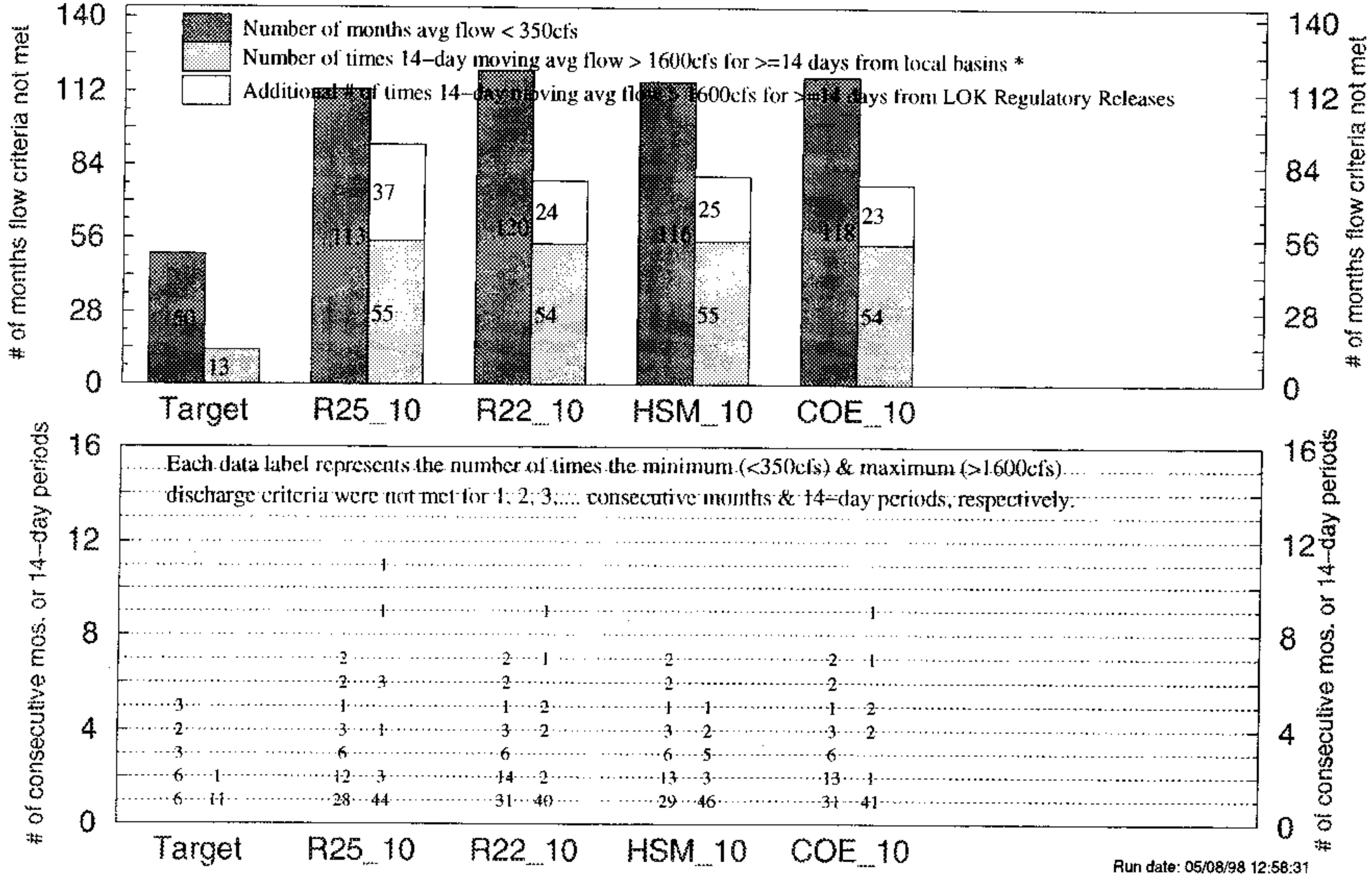
D-10

Wed Apr 30 14:07:58 1997

Environmental, Level III, LOK
SFWMM Simulation

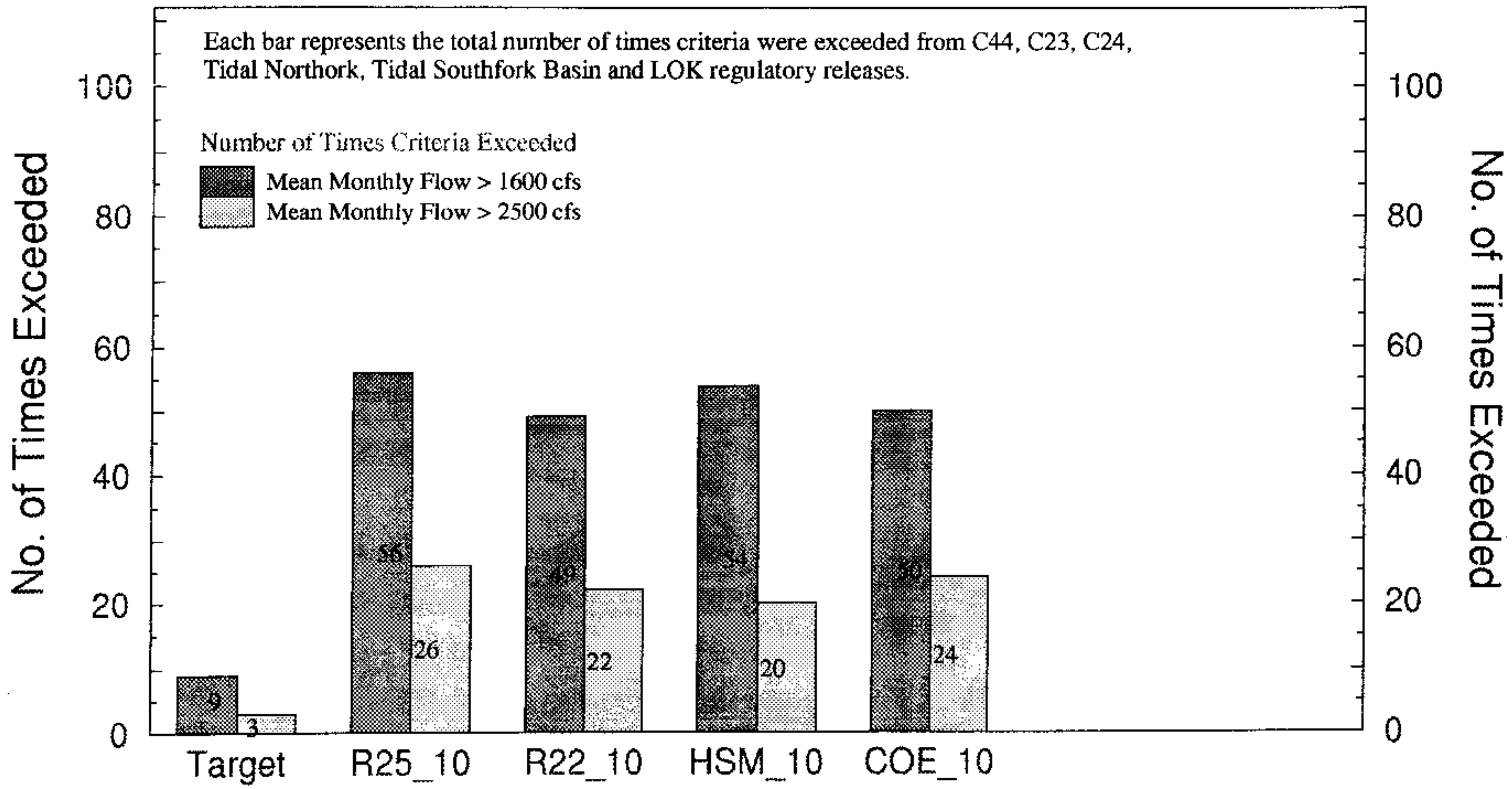
Performance Measures for the
Caloosahatchee and St. Lucie Estuaries

Number of times Salinity Envelope Criteria were NOT met for the St. Lucie Estuary



Run date: 05/08/98 12:58:31
For Planning Purposes Only
SFWMM V3.2

Number of Times High Discharge Criteria (mean monthly flows > 1600 & 2500 cfs) were exceeded for the St. Lucie Estuary

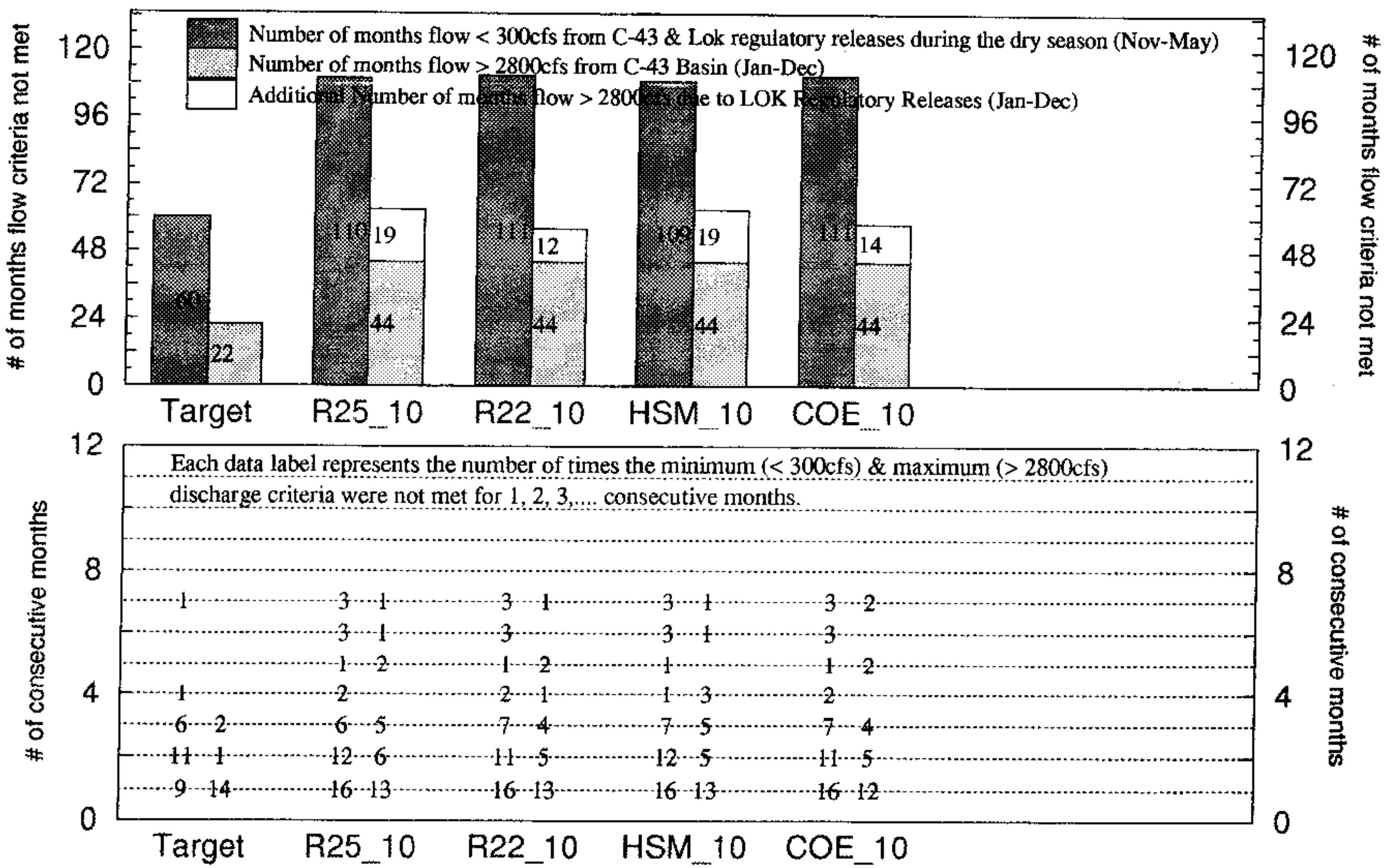


Note: A favorable maximum monthly flow was developed for the estuary (1600 cfs) that will theoretically provide suitable salinity conditions which promote the development of important benthic communities (eg. oysters & shoalgrass). Mean monthly flows above 2500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota.

Wed Apr 30 14:20:47 1997

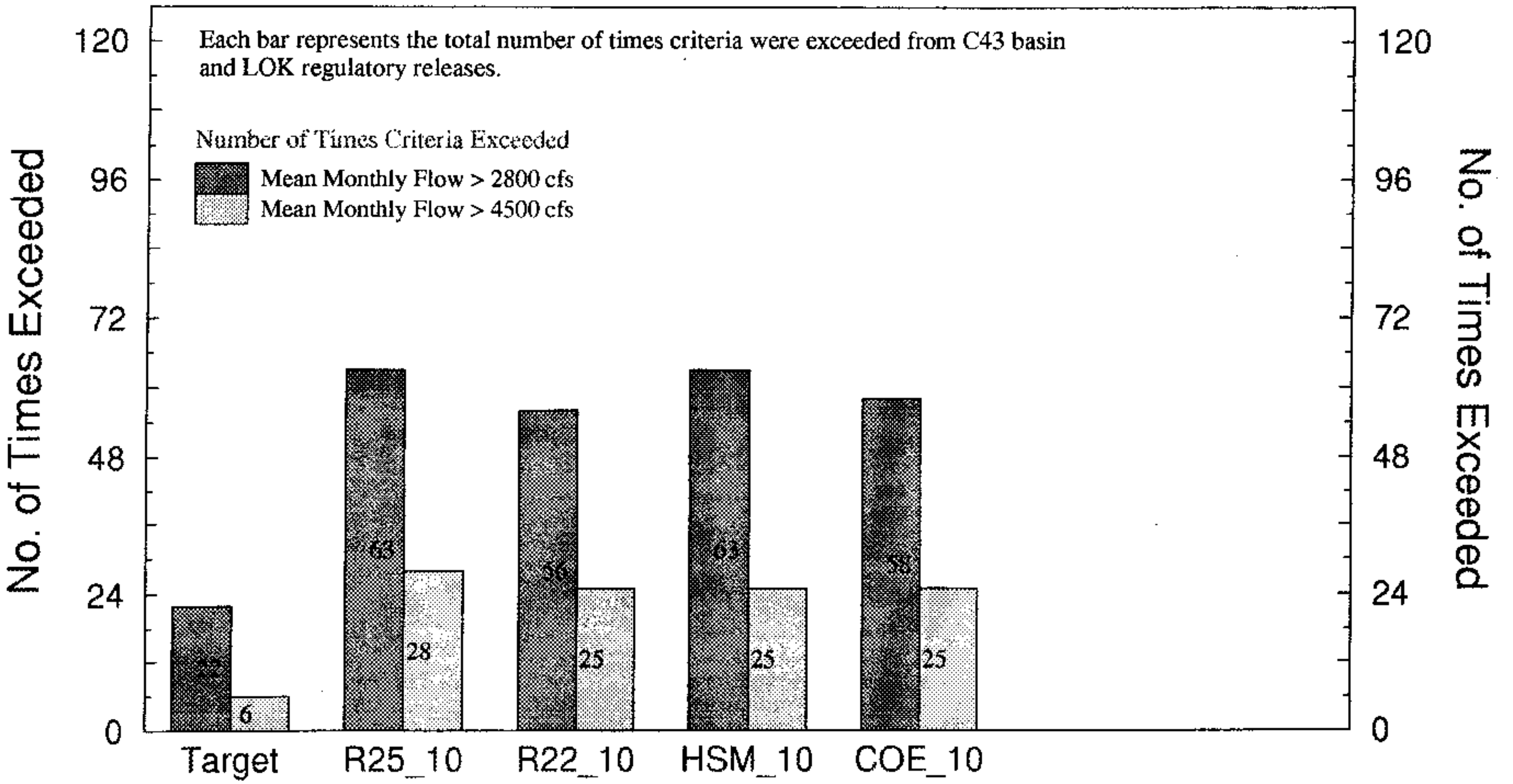
Environmental, Level I, LOK
SFWMM Simulation

Number of times Salinity Envelope Criteria were NOT met for the Caloosahatchee Estuary (mean monthly flows 1965 - 1995)



D-13

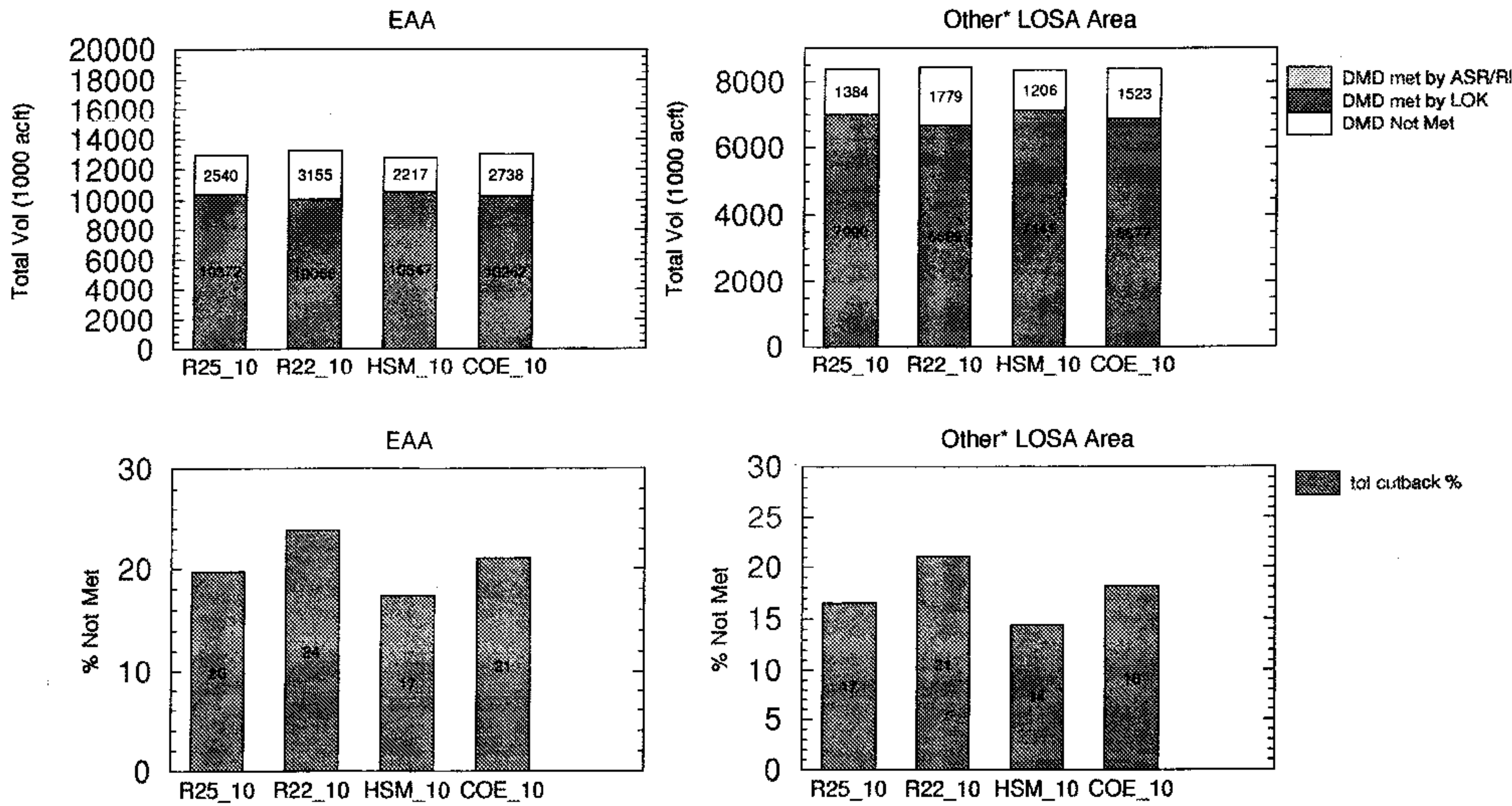
Number of Times High Discharge Criteria (mean monthly flows > 2800 & 4500 cfs) were exceeded for the Caloosahatchee Estuary



D-14

Performance Measures for the
Lake Okeechobee Service Area

Total EAA/LOSA Irrigation Demands and Demands Not Met
for the 1965 - 1995 Simulation Period

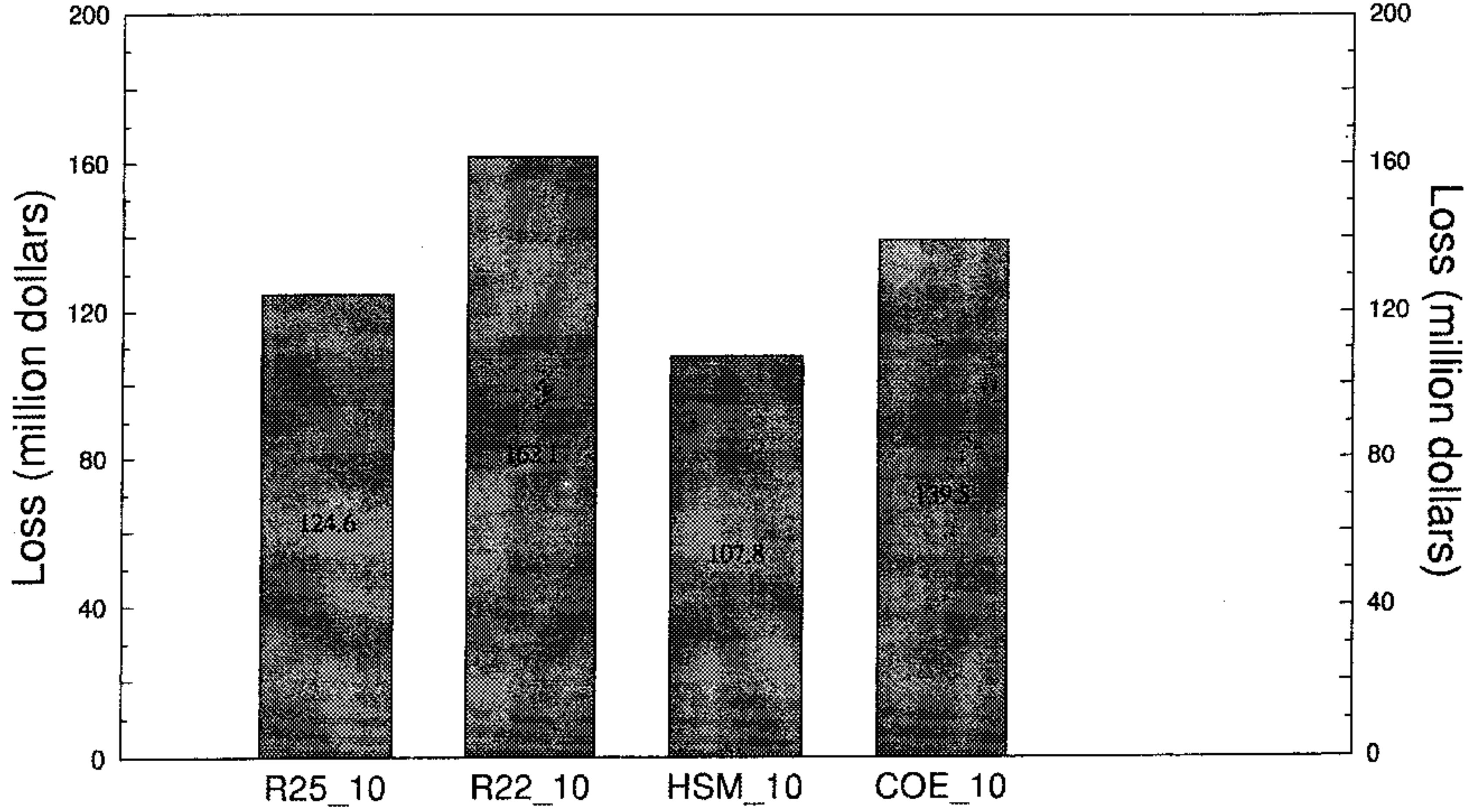


*Other Lake Service SubAreas Outside the Plan Boundaries (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

Wed Apr 30 14:22:17 1997

Water Supply, Level I, EAA/LOSA
SFWMM Simulation

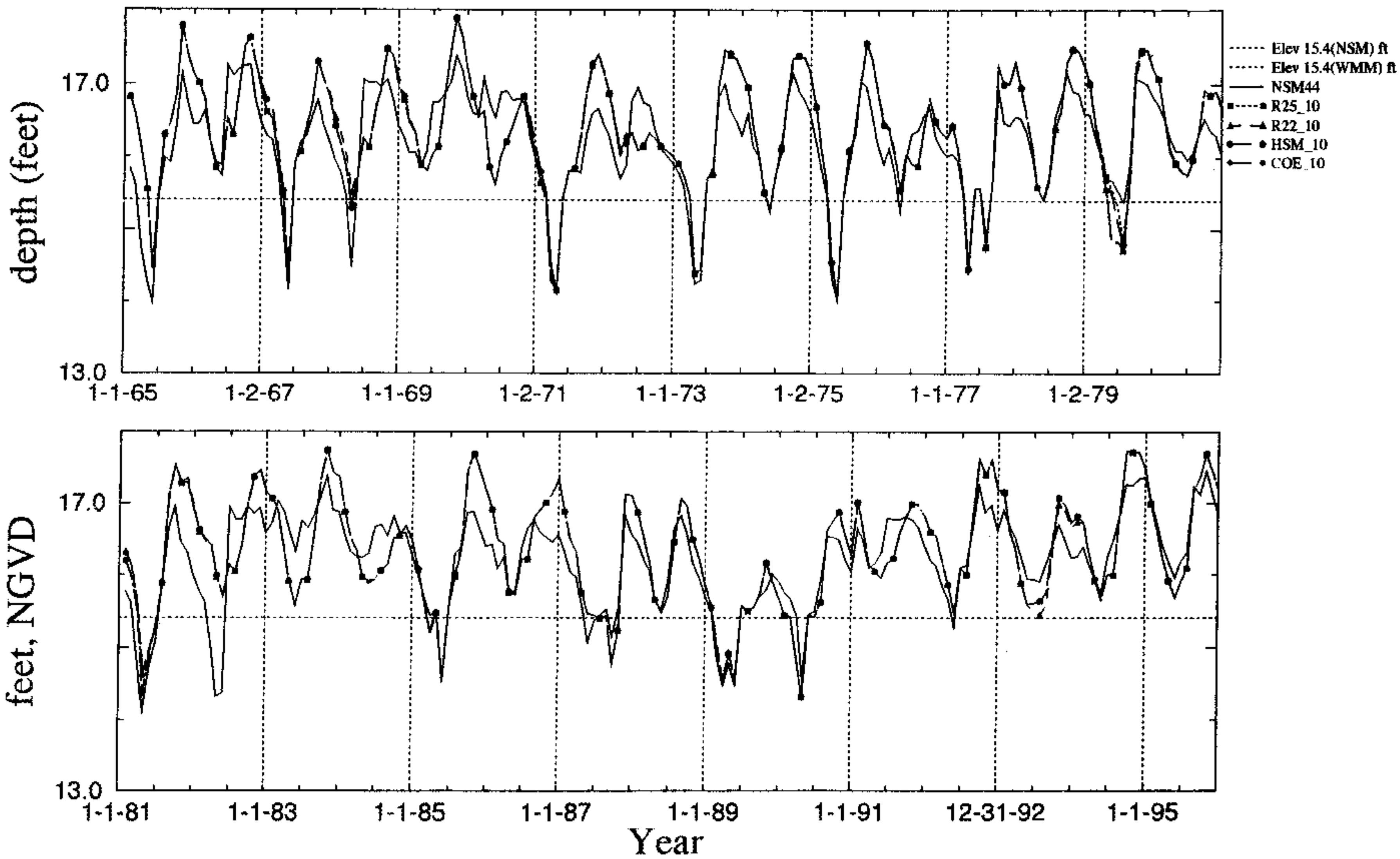
EAA IRRIGATED AREA ECONOMIC LOSSES
Total Losses Due to ET Reduction for 31 yr. simulation



Note: Losses are based on Yield Reductions for Sugarcane in the EAA.
Sugarcane acreage(acres): 529,920(1990) 491,520(2010)

Performance Measures for the
Everglades WCAs

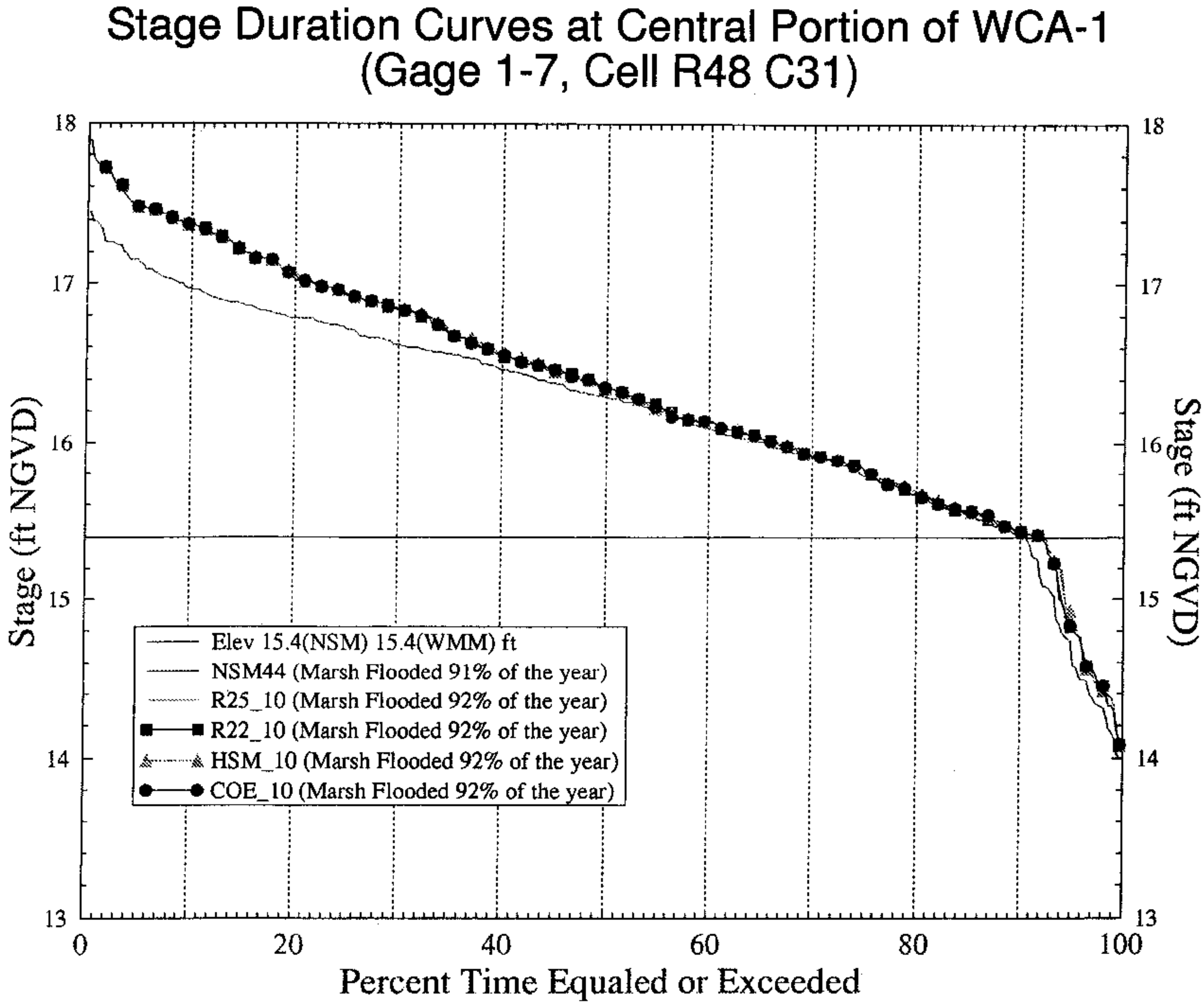
Stage Hydrograph at Central Portion of WCA-1 (Gage 1-7, Cell R48 C31)



D-17

Wed Apr 30 12:40:35 1997

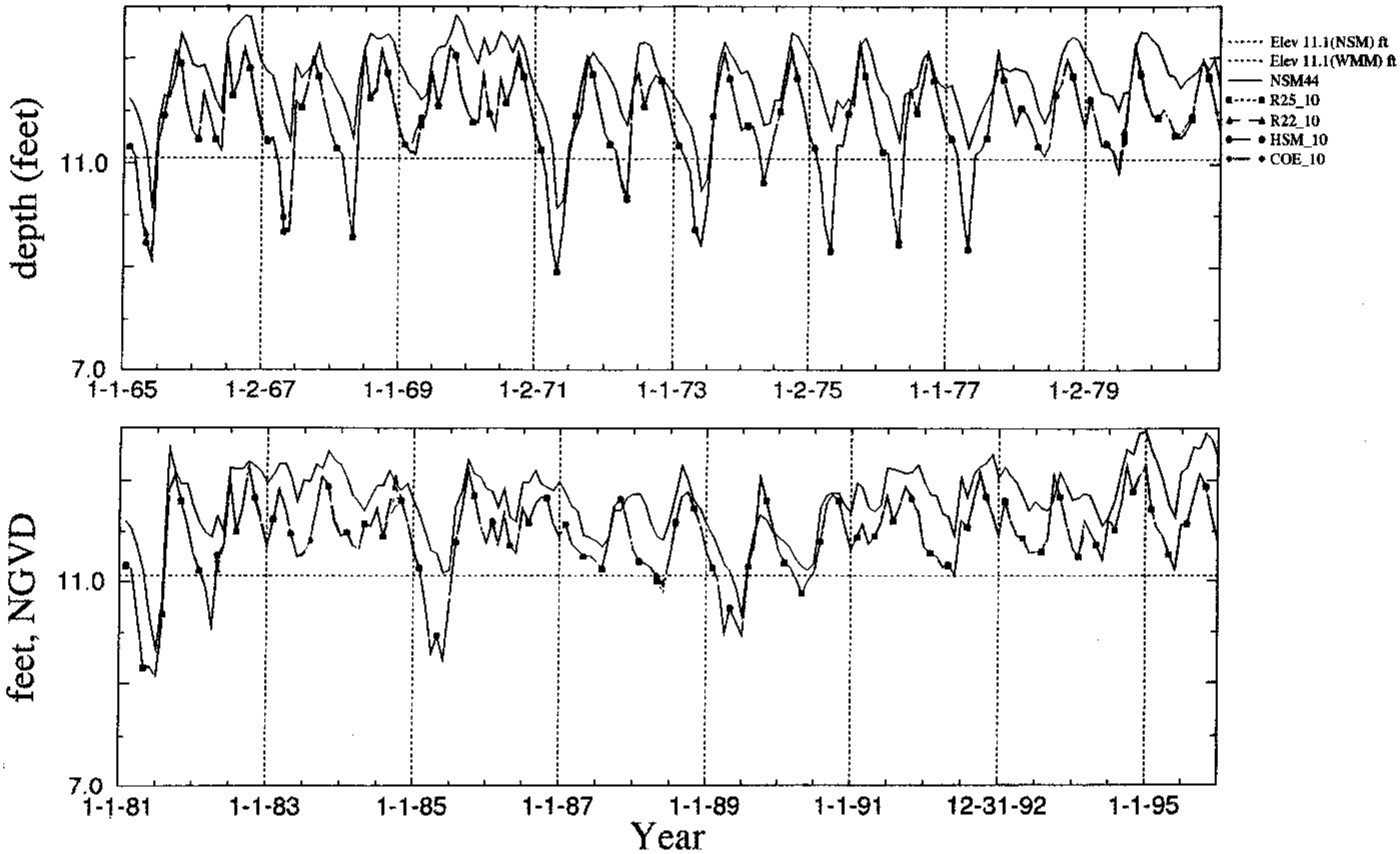
Environmental Water Supply / SFWMM Simulation



Wed Apr 30 12:38:51 1997

Environmental, Level II, WCA
SFWMM Simulation

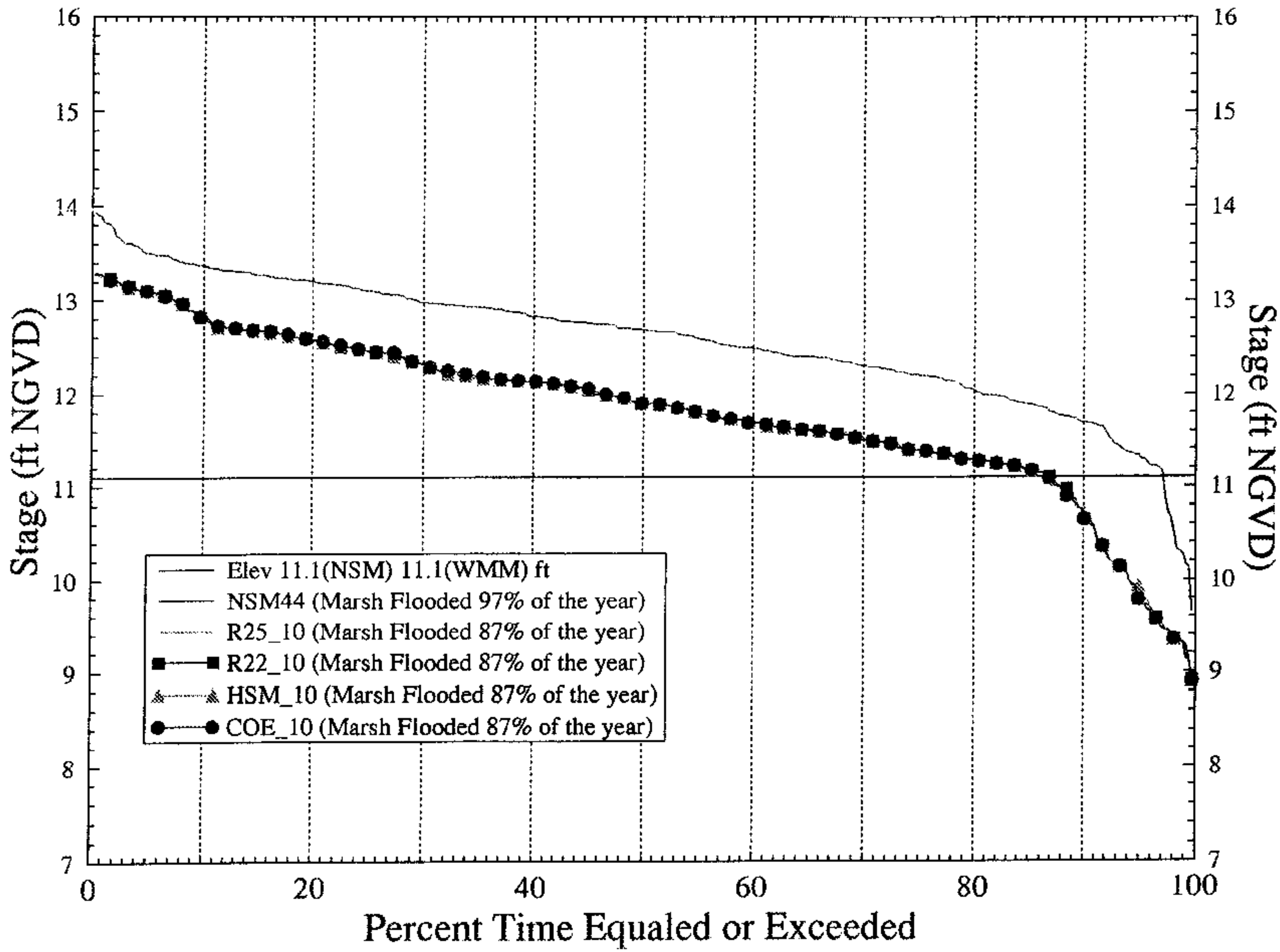
Stage Hydrograph for Central Portion of WCA-2A
(Gage 2-17, Cell R40 C29)



Wed Apr 30 12:39:14 1997

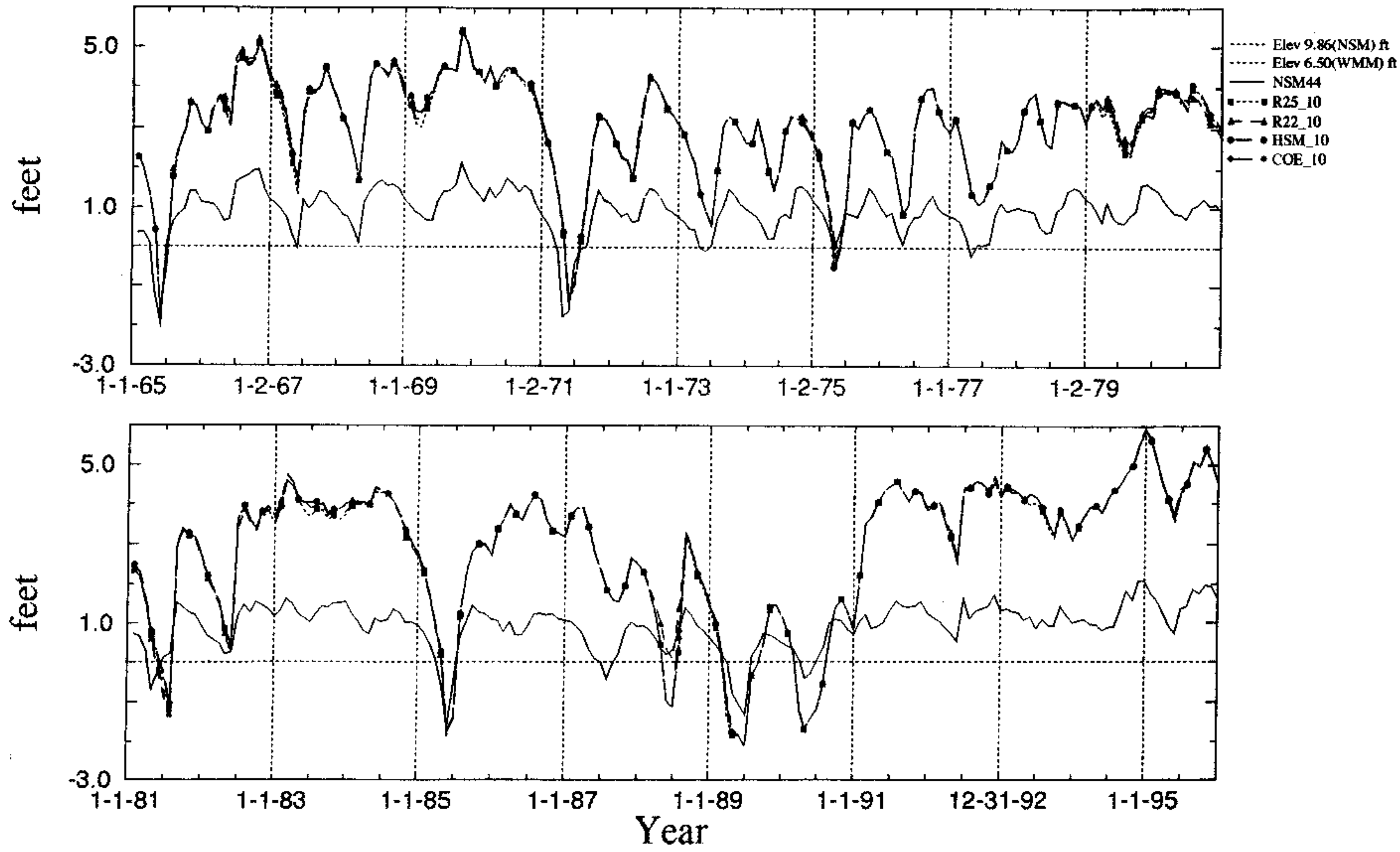
SFWMM Simulation

Stage Duration Curves at Central Portion of WCA-2A (Gage 2-17, Cell R40 C29)



c2-4

Normalized Stage Hydrograph at South End of WCA-2B (Gage 2B-21, R35 C30)



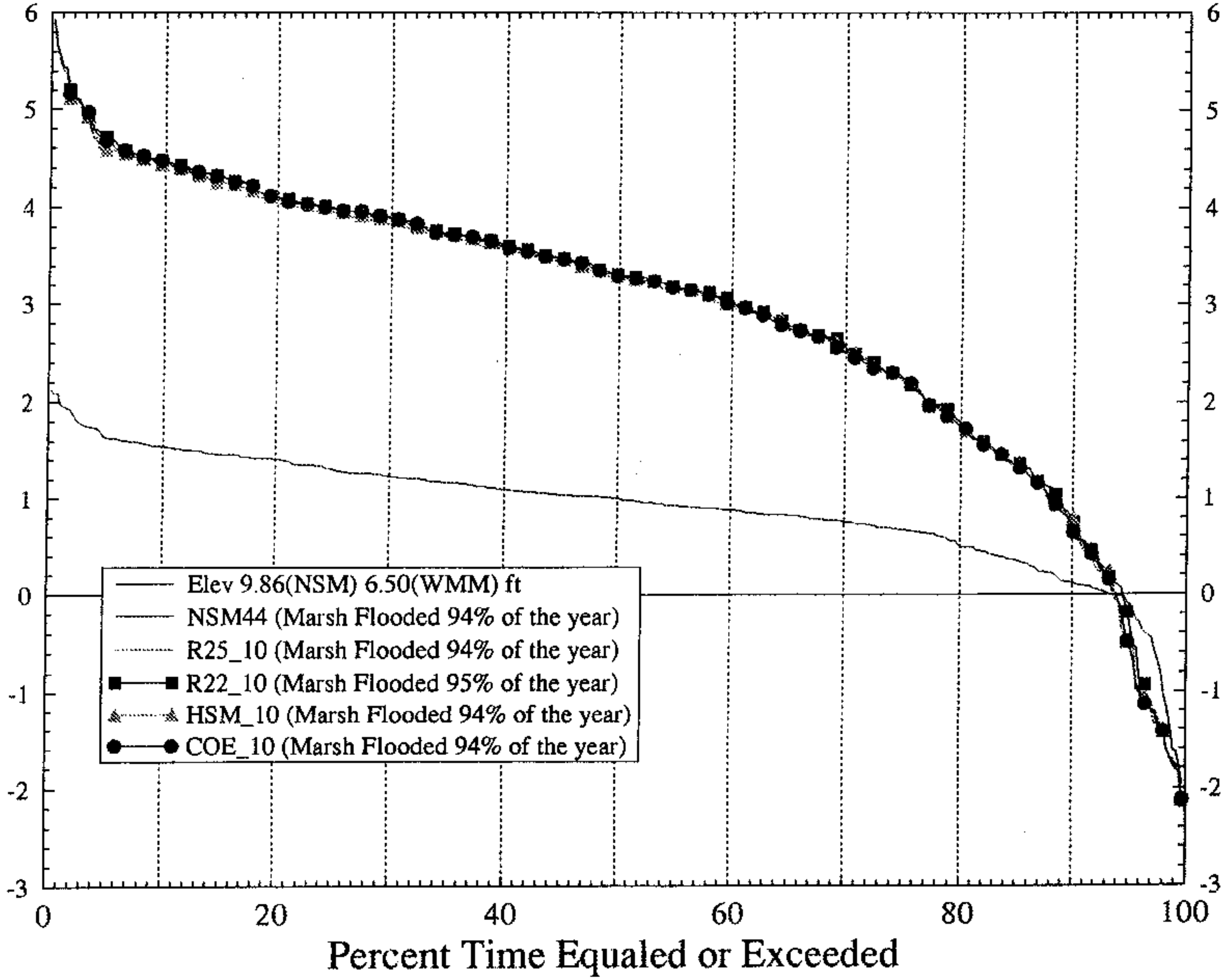
D-21

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Wed Apr 30 12:33:02 1997

Environmental, WCA, ENR
SFWMM Simulation

Normalized Stage Duration Curves at South End of WCA-2B (Gage 2B-21, R35 C30)

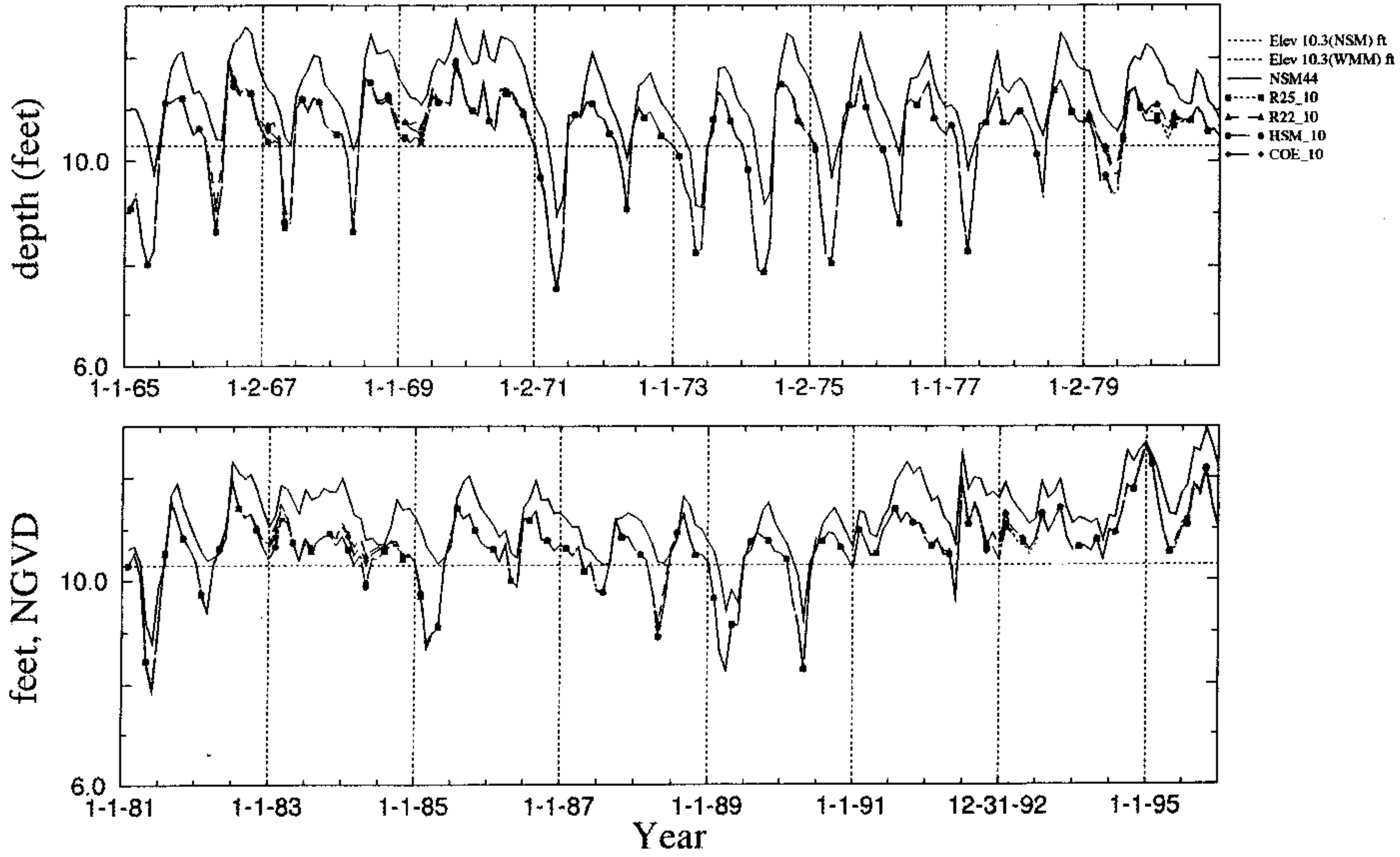


Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Wed Apr 30 12:32:44 1997

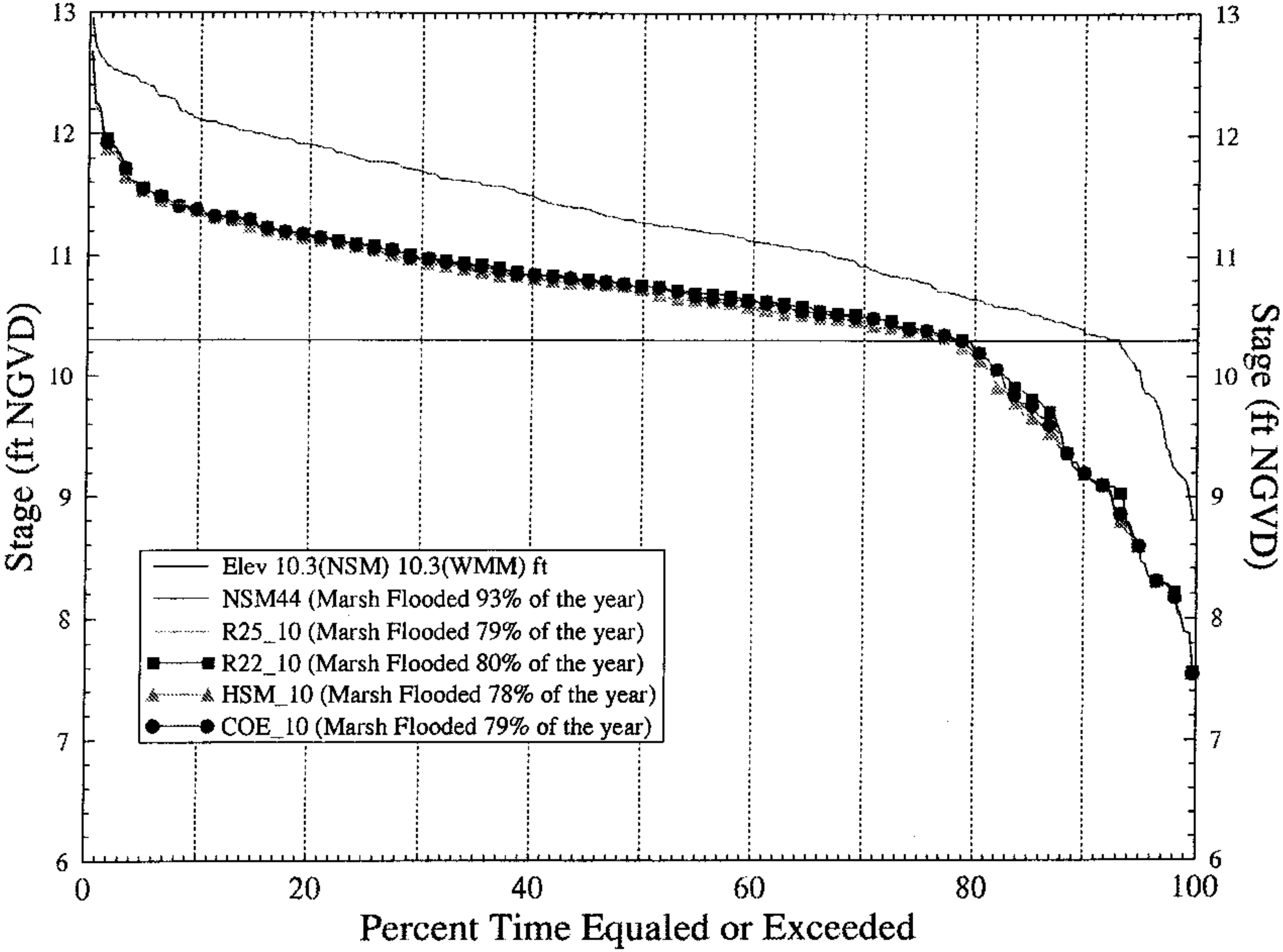
Environmental, Level II, WCA
SFWMM Simulation

Stage Hydrograph for North End of WCA-3A
(Gage 3A-2, West of Miami Canal, R36 C18)



D-23

Stage Duration Curves at North End of WCA-3A
(Gage 3A-2, Cell R36 C18, West of Miami Canal)

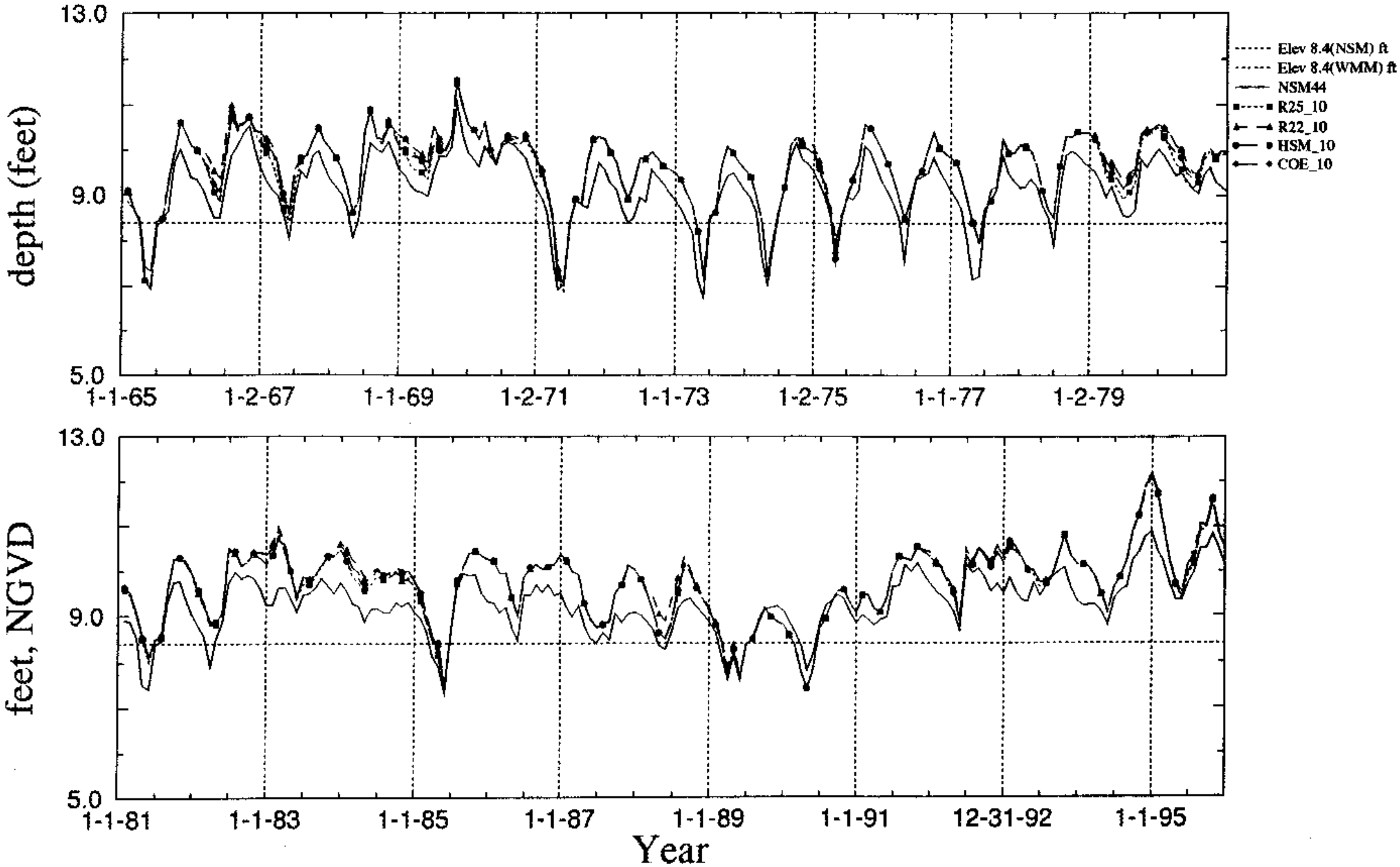


D-24

Wed Apr 30 12:18:26 1997

Environmental, Level II, WCA
SFWMM Simulation

Stage Hydrograph for Central Portion of WCA-3A
(Gage 3A-4, Cell R29 C21)

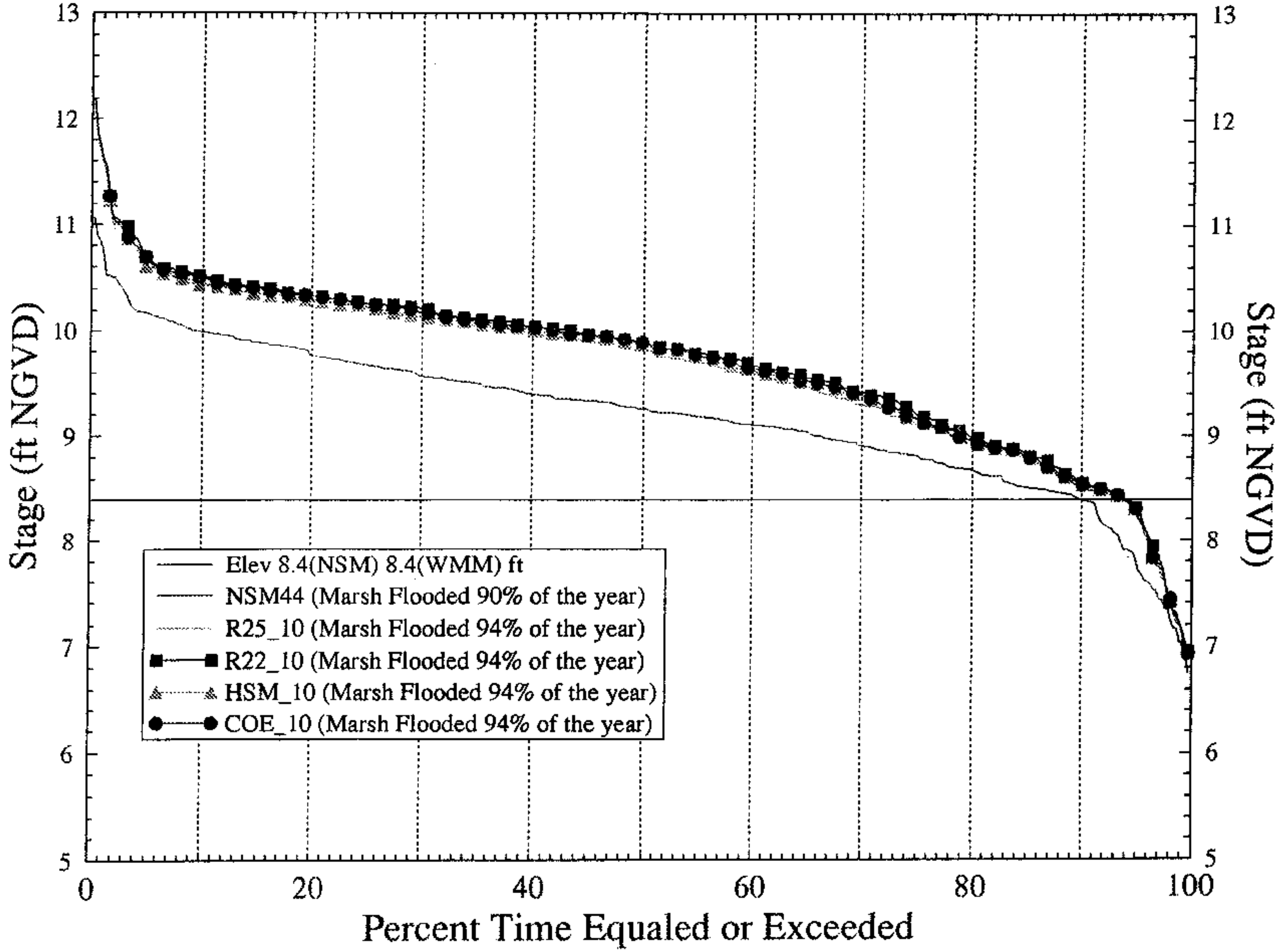


D-25

Wed Apr 30 12:39:48 1997

SFWMM Simulation

Stage Duration Curves at Central Portion of WCA-3A
(Gage 3A-4, Cell R29 C21)

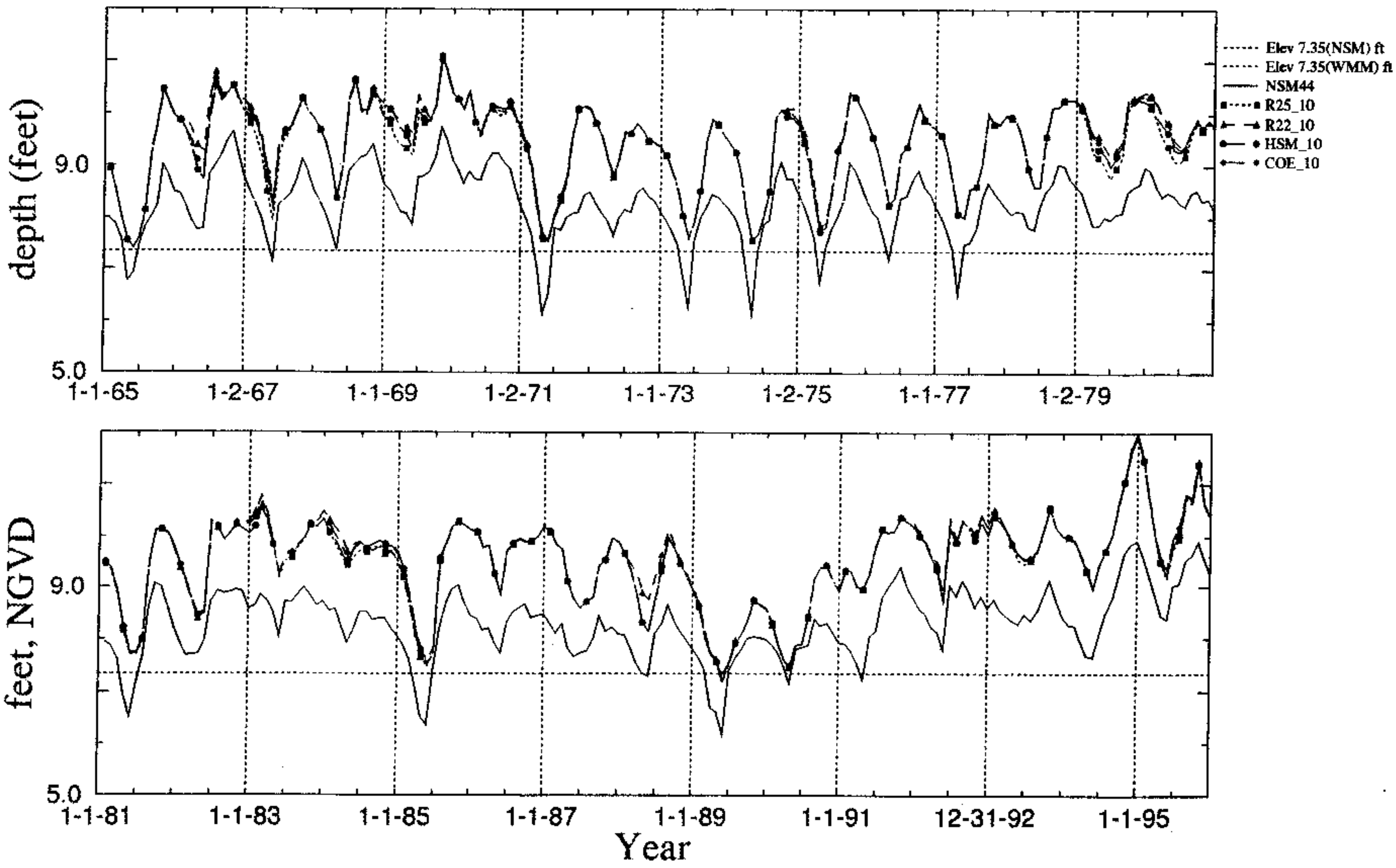


D-26

Wed Apr 30 12:37:57 1997

Environmental, Level II, WCA
SFWMM Simulation

Stage Hydrograph for South End of WCA-3A
(Gage 3A-28, Cell R24 C19)

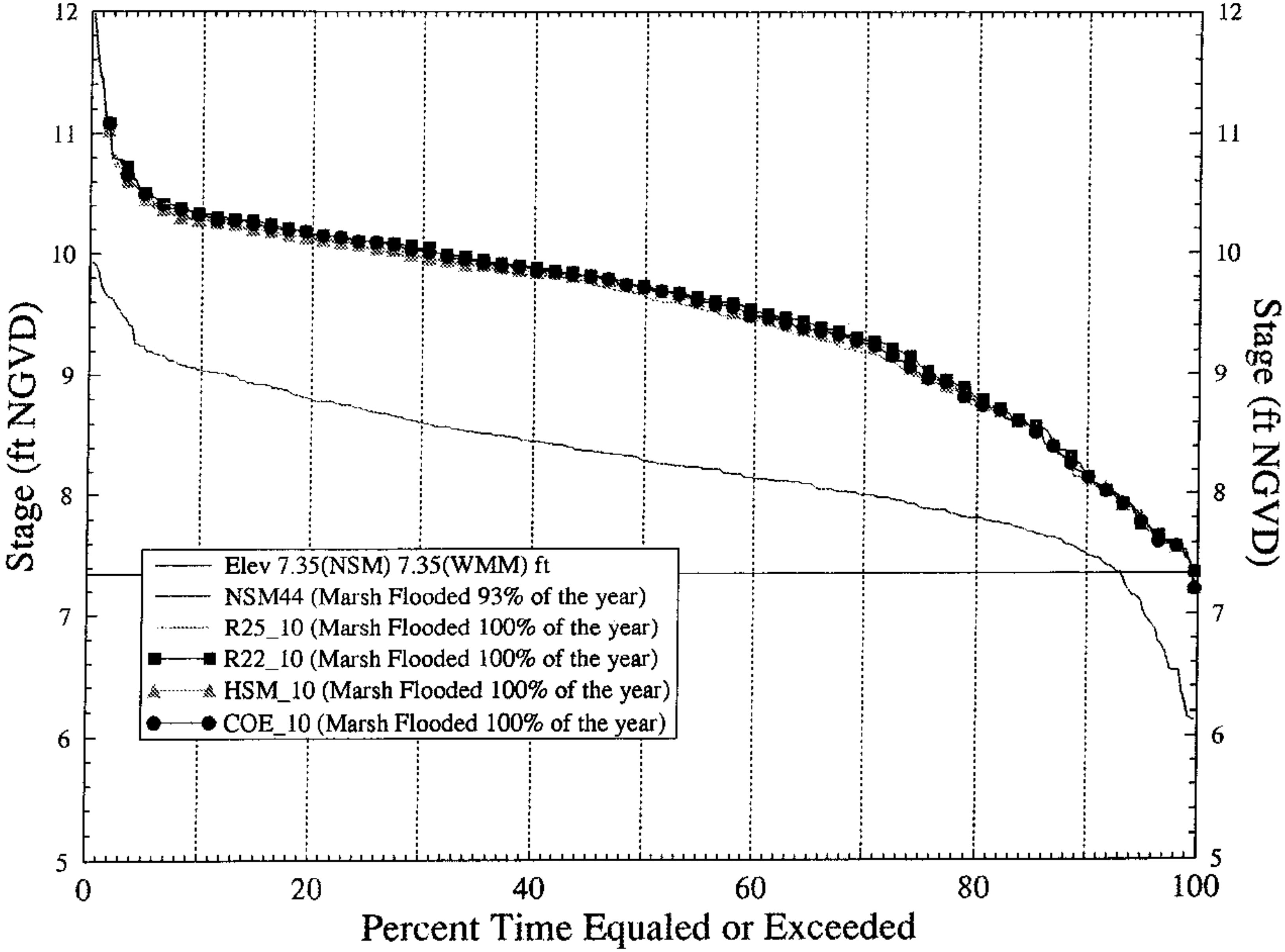


D-27

Wed Apr 30 12:39:35 1997

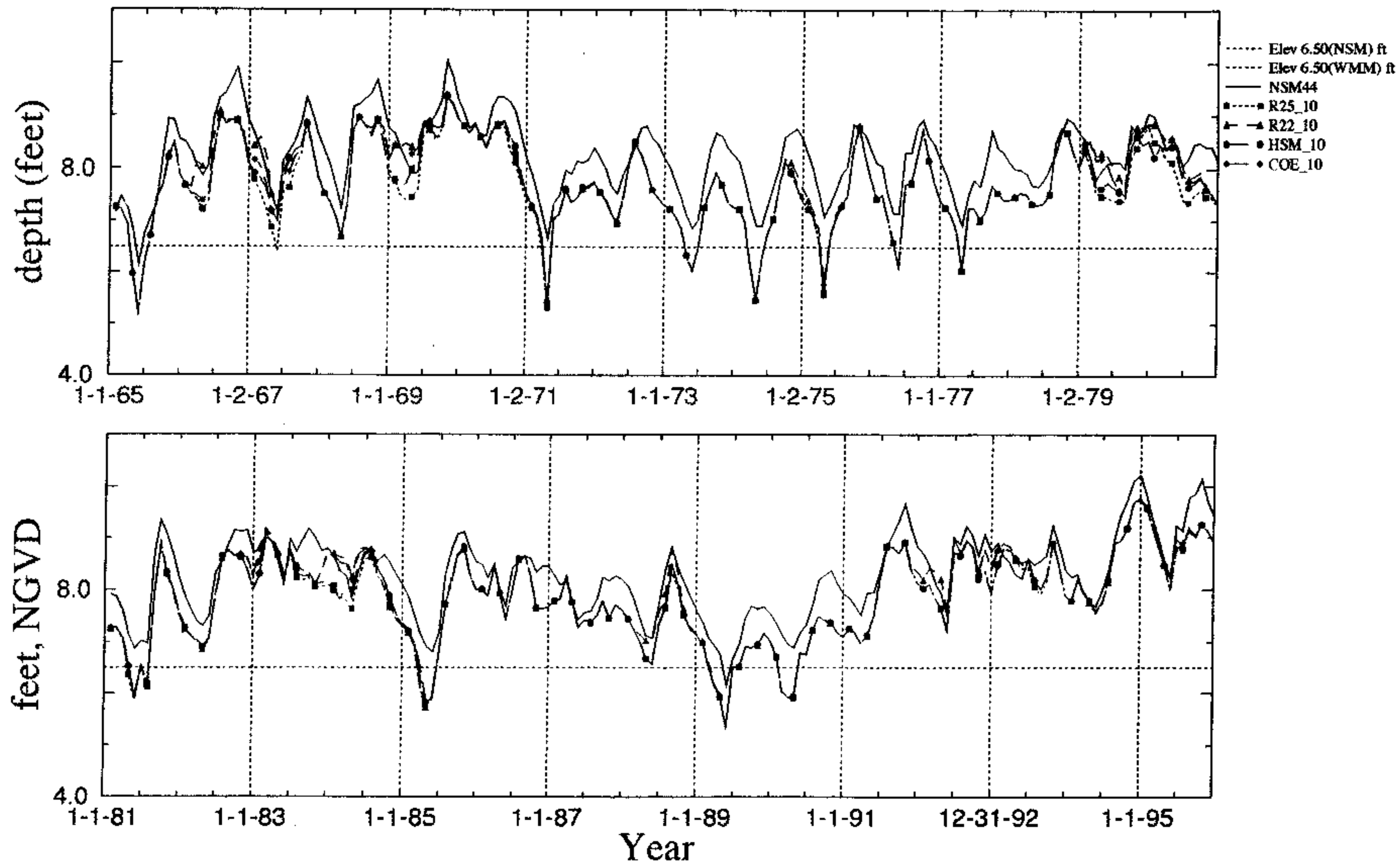
Environmental WCA/ESR
SFWMM Simulation

Stage Duration Curves at South End of WCA-3A
(Gage 3A-28, Cell R24 C19)



82-Q

Stage Hydrograph for North-End of WCA-3B
(Gage 3B-2, Cell R25 C25)

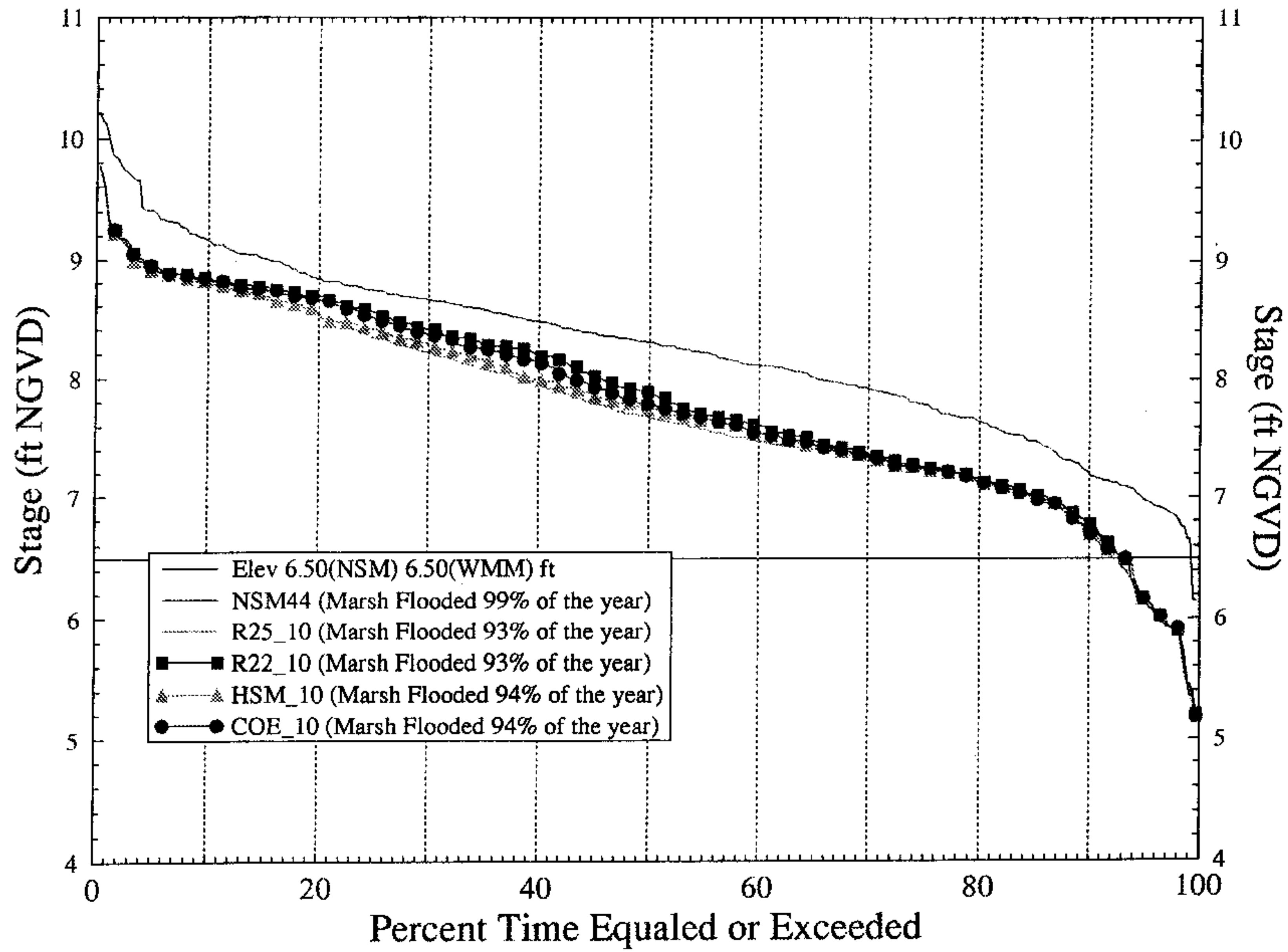


D-29

Wed Apr 30 12:39:58 1997

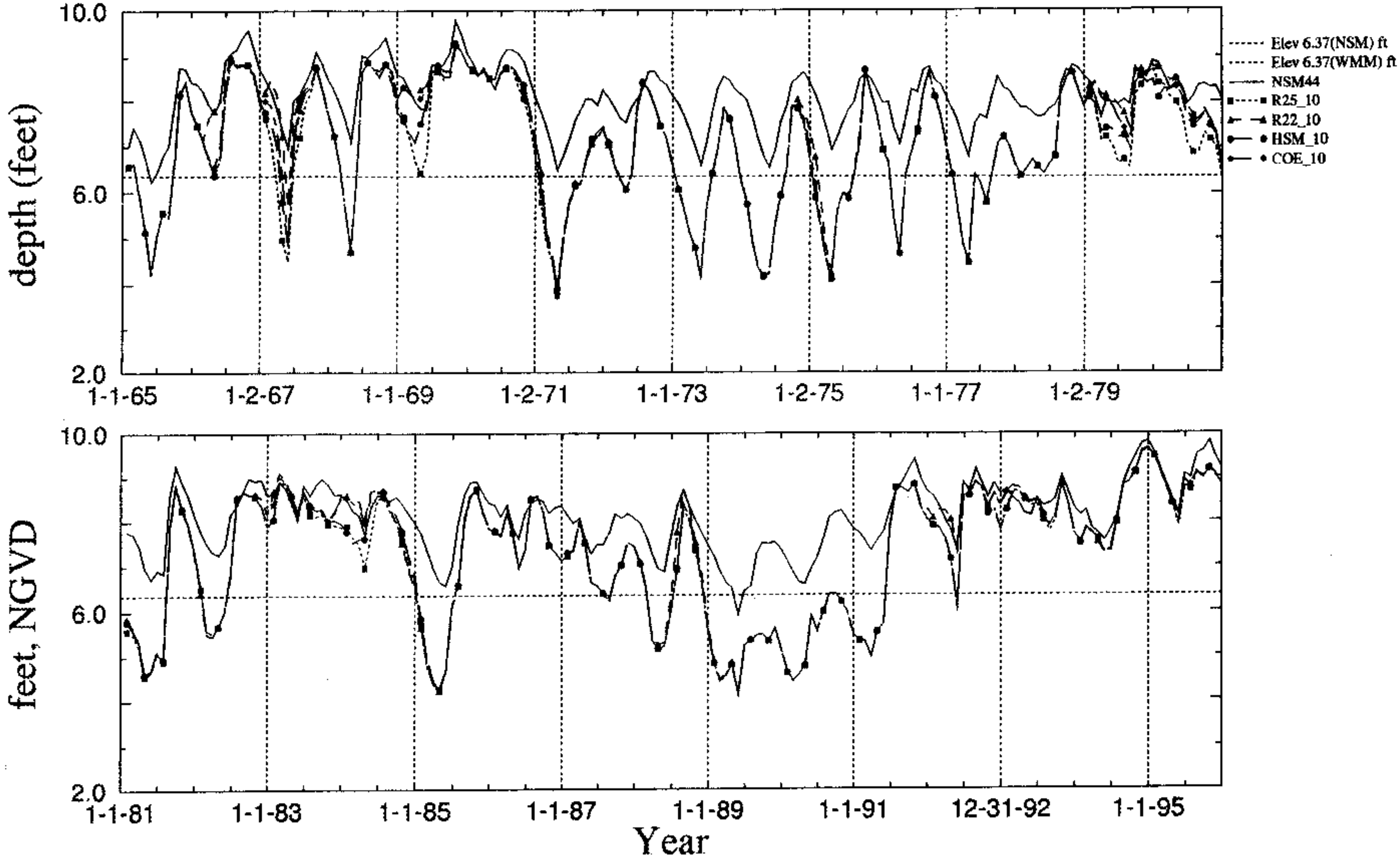
SFWMM Simulation

Stage Duration Curves at North-End of WCA-3B
(Gage 3B-2, Cell R25 C25)



D-30

Stage Hydrograph for South End of WCA-3B
(Gage 3B-SE, Cell R23 C26)

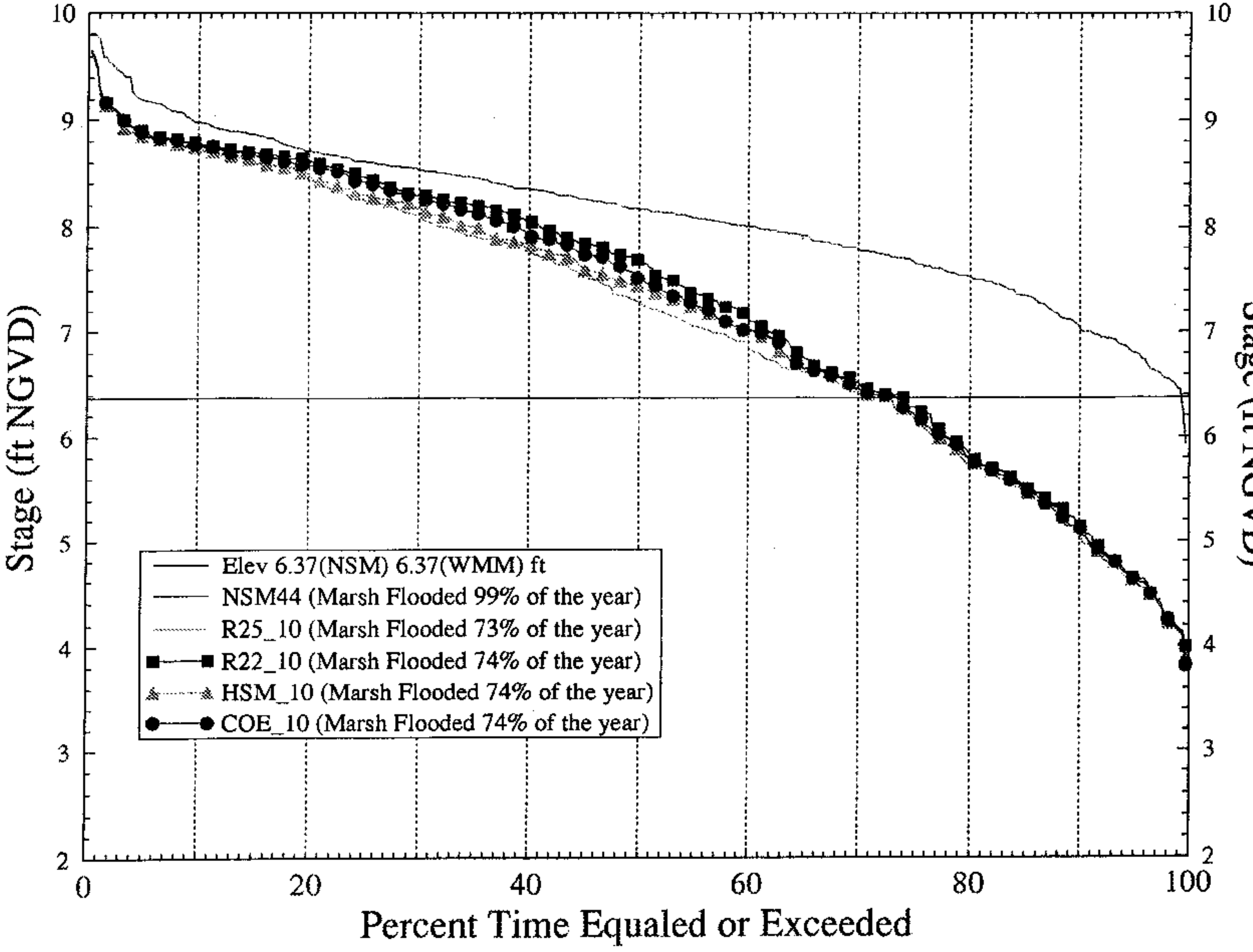


D-31

Wed Apr 30 12:40:23 1997

Environmental/WCA/ENR
SFWMM Simulation

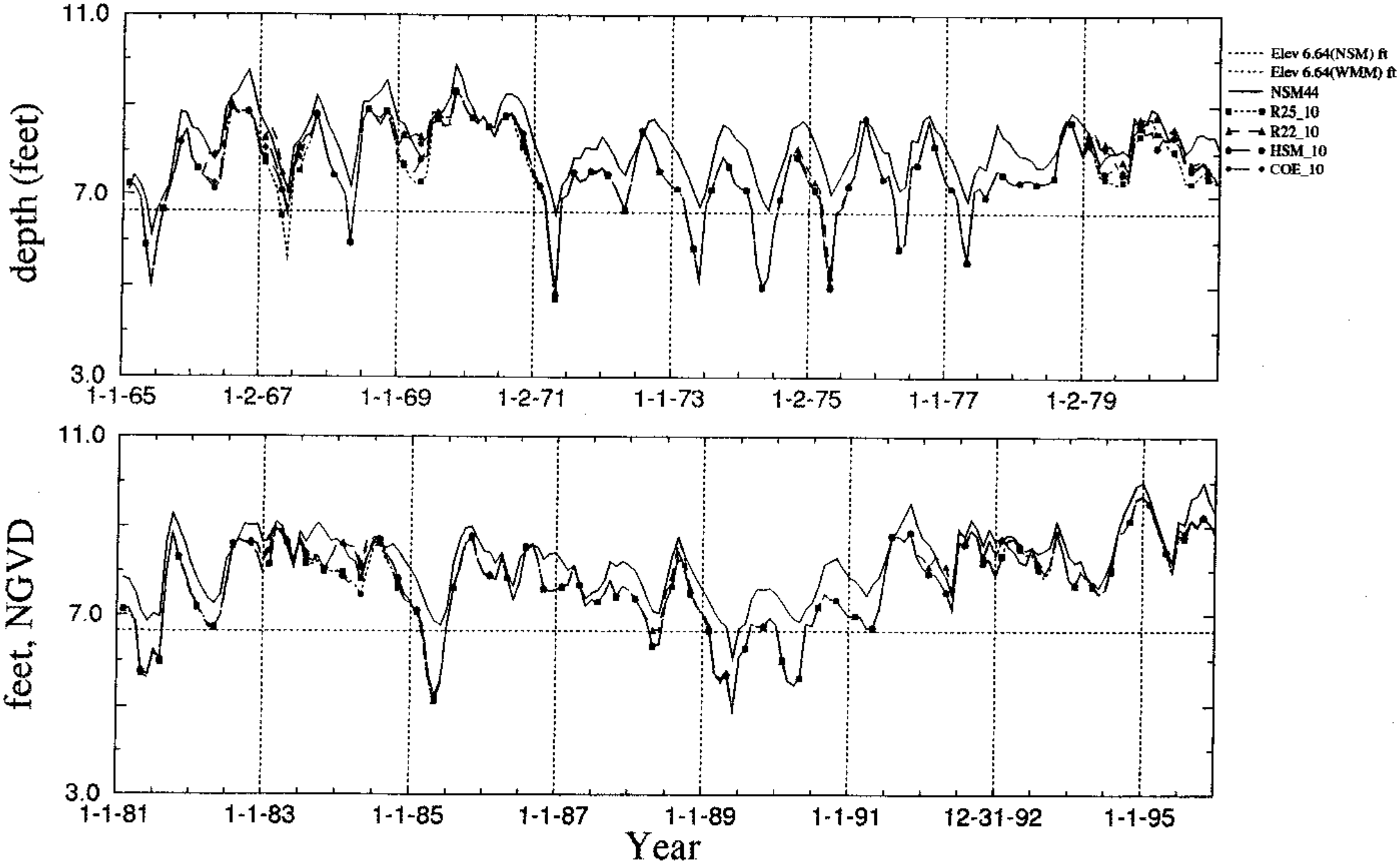
Stage Duration Curves at South End of WCA-3B
(Gage 3B-SE, Cell R23 C26)



Wed Apr 30 12:38:37 1997

Environmental, Level II, WCA

Stage Hydrograph at South End of WCA-3B
(Cell R24 C25)

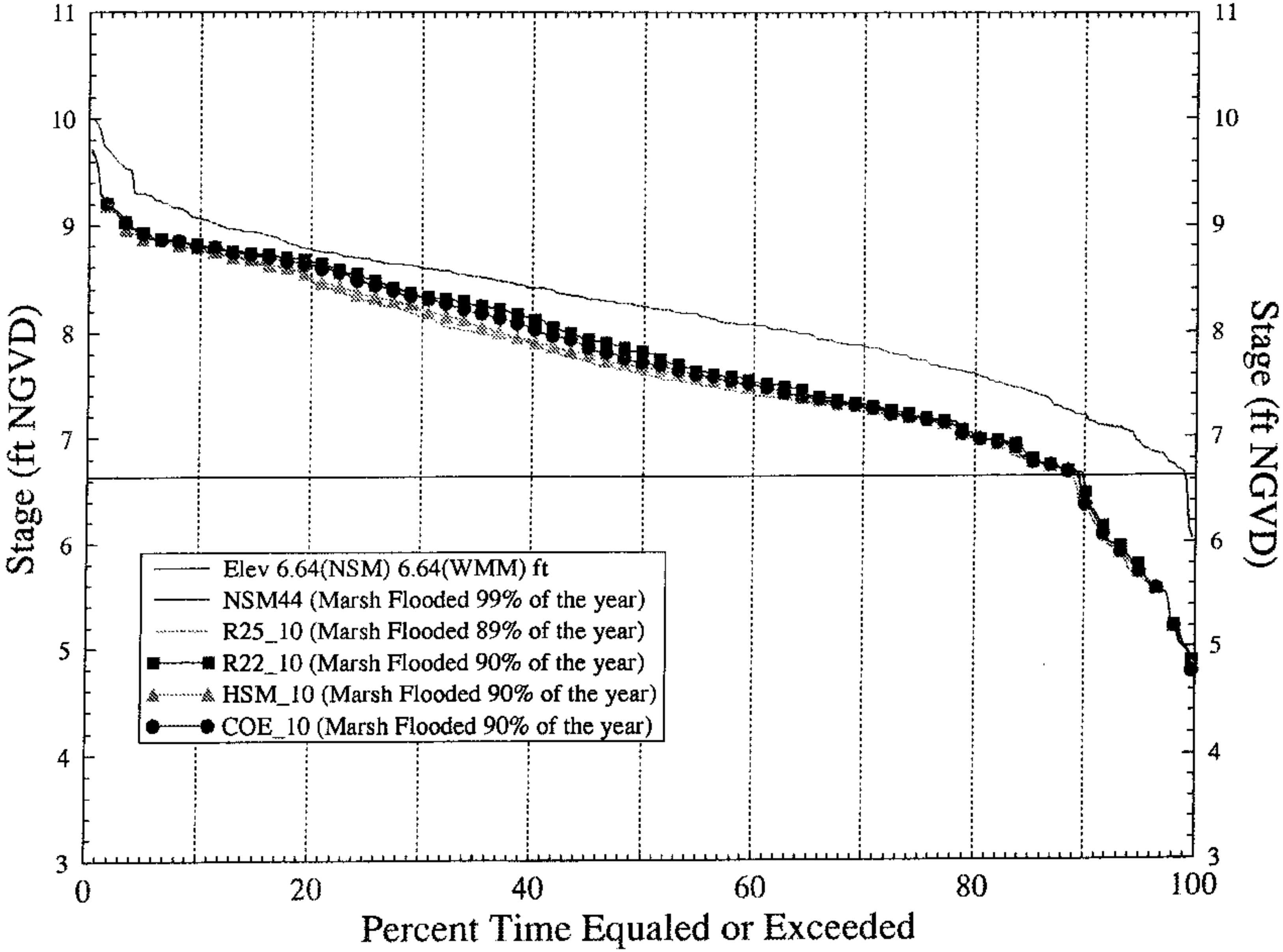


D-33

Wed Apr 30 12:40:10 1997

Environmental Iss/WDA/ZDR
SFWMM Simulation

Stage Duration Curves at South End of WCA-3B
(Cell R24 C25)

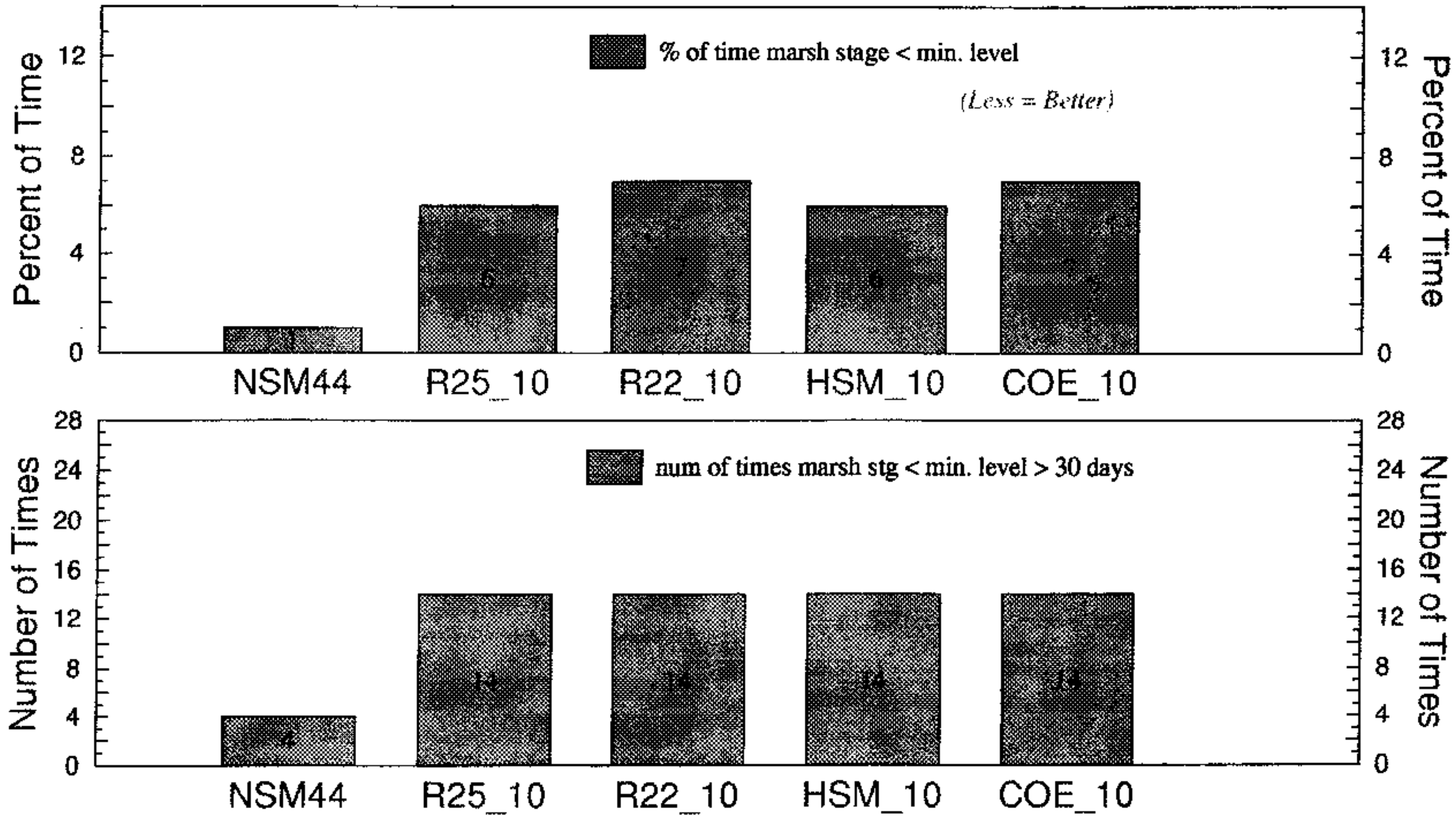


D-34

Wed Apr 30 12:38:27 1997

Environmental, Level II, WCA
SFWMM Simulation

% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
(Gage 2-17, Cell R40 C29, Proposed Min Lvl 1 ft below ground)

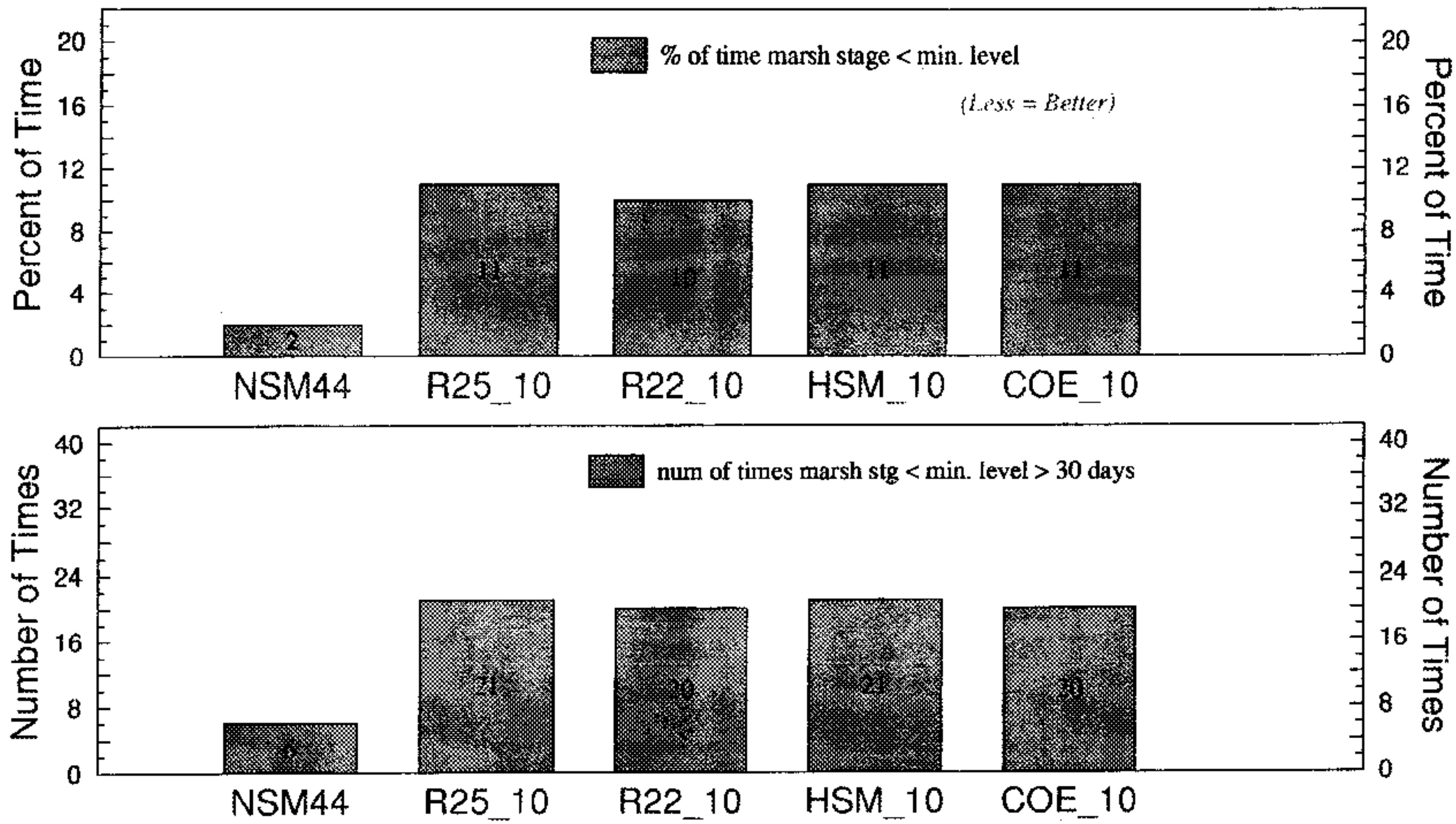


D-35

Wed Apr 30 14:30:01 1997

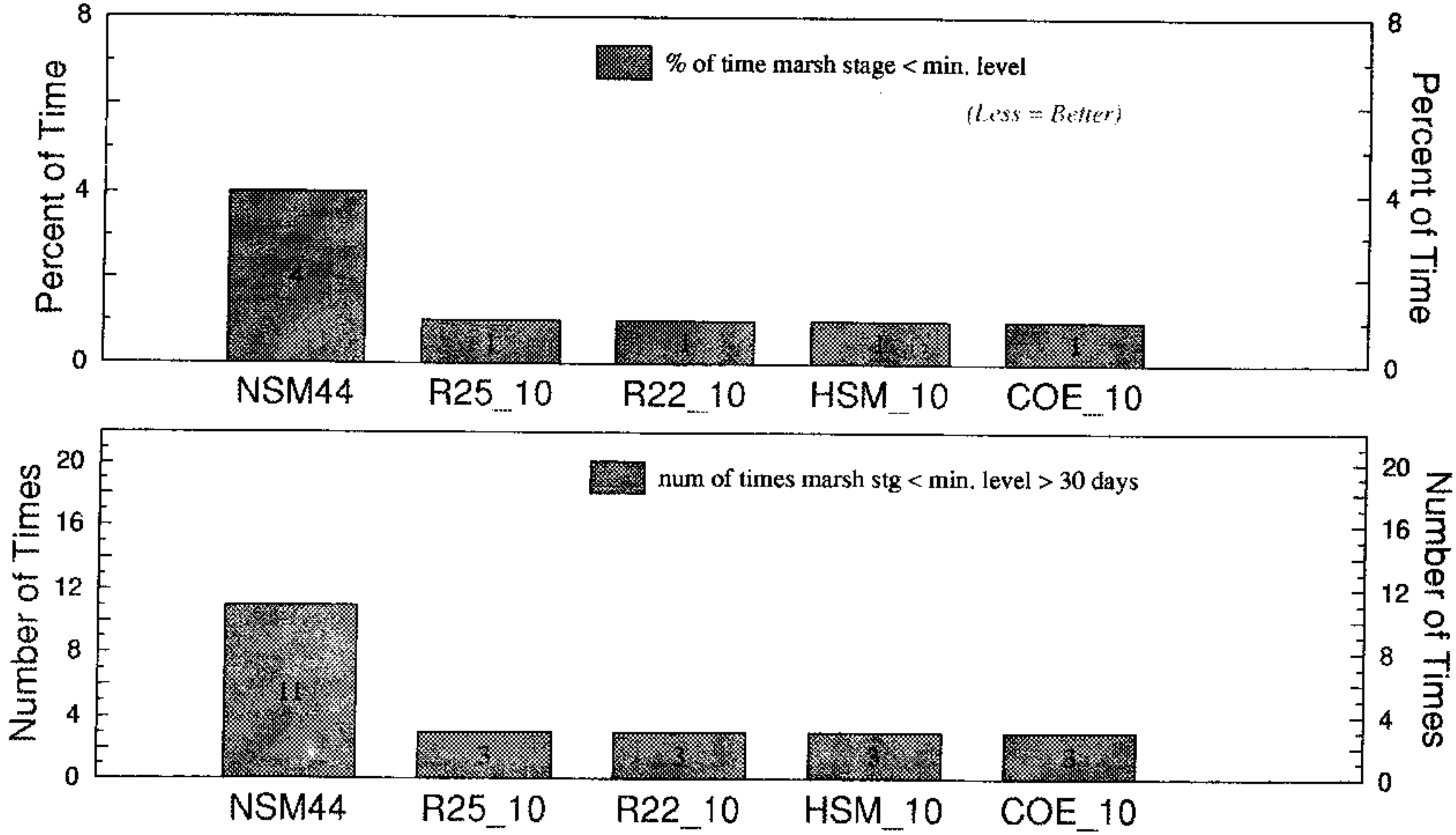
SFWMM Simulation

% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
(Gage 3A-2, Cell R36 C18, Proposed Min Lvl 1 ft below ground)



D-36

% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
Gage 3A-3, Cell R37 C25, Proposed Min Lvl 1 ft below ground

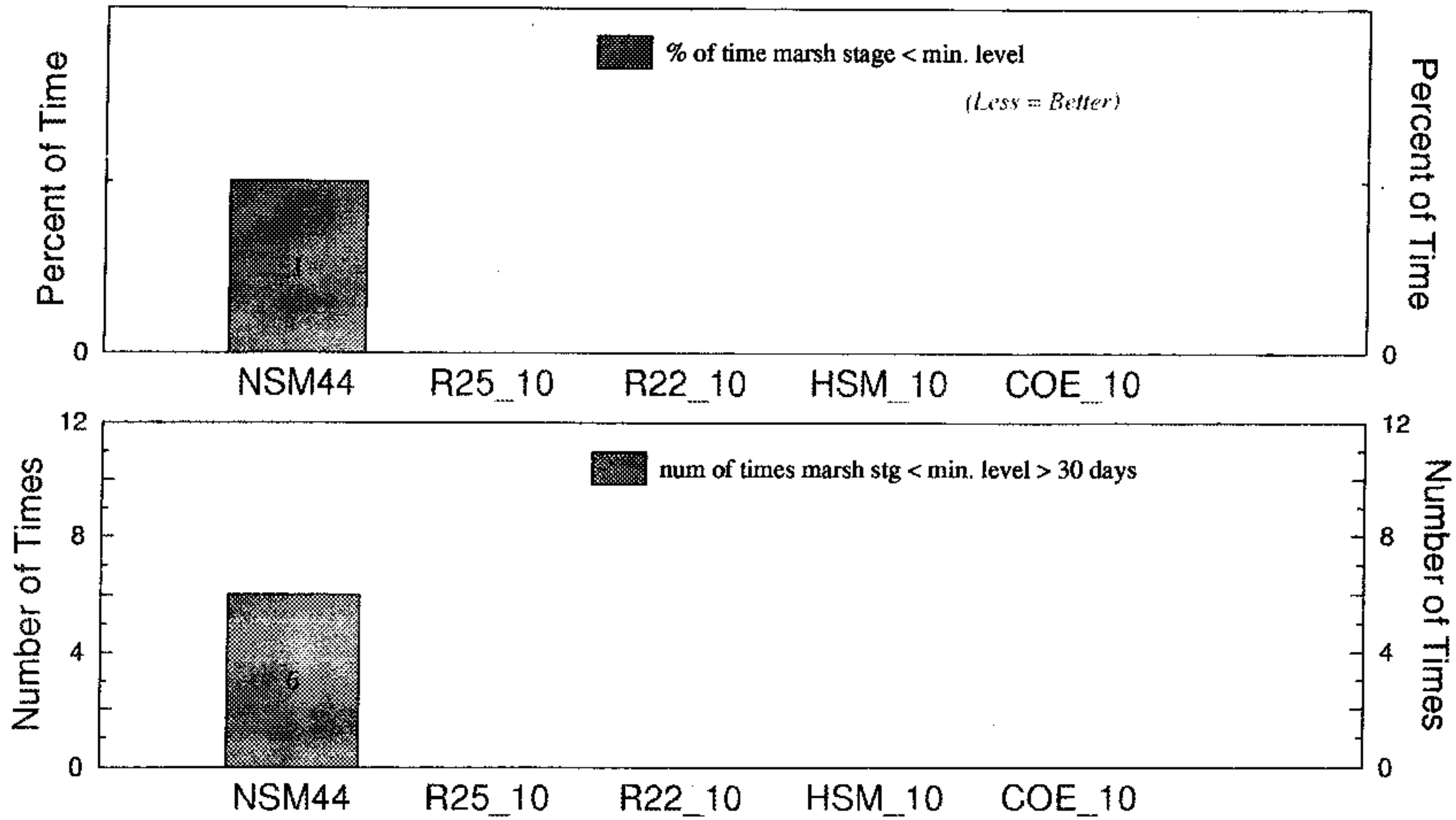


D-37

Wed Apr 30 14:31:42 1997

SFWMM Simulation

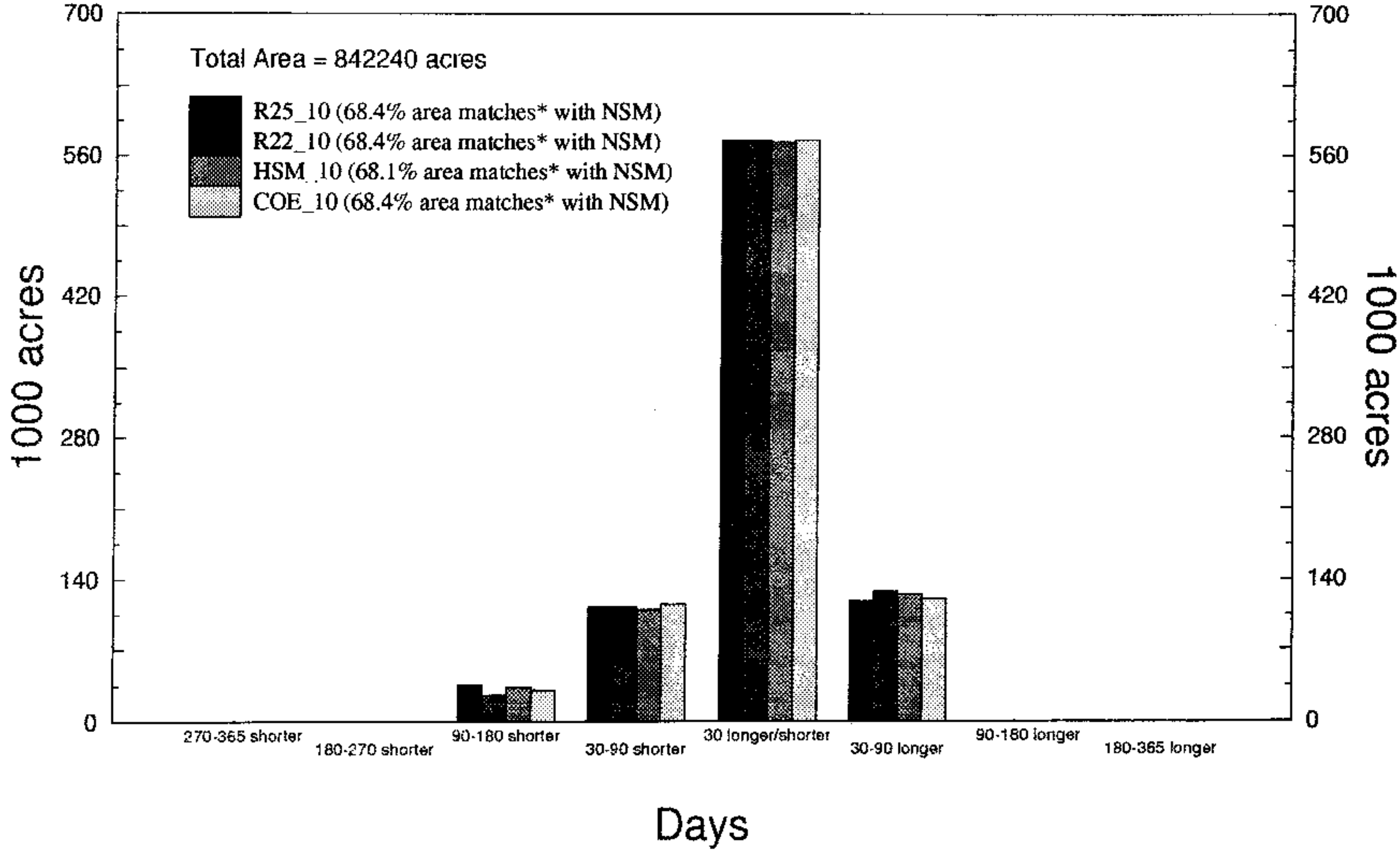
% of Time Marsh Stage < Minimum Level Criteria and Occurences > 30 days
(Gage 3A-28, Cell R24 C19, Proposed Min Lvl 1 ft below ground)



D-38

Wed Apr 30 14:31:59 1997

Mean NSM hydroperiod matches for the WCA SYSTEM for the 31 yr. simulation



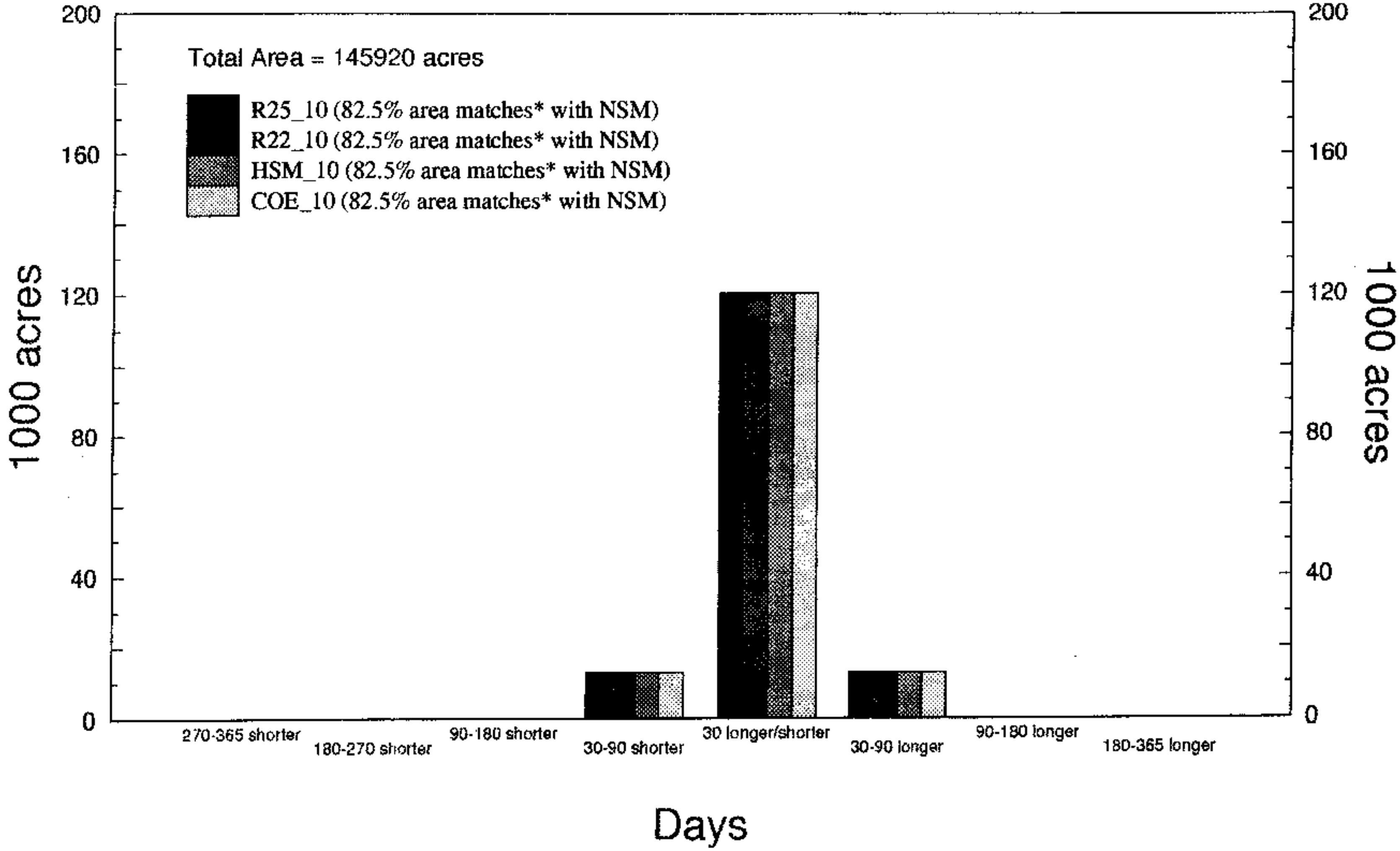
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wed Apr 30 14:33:02 1997

SFWMM Simulation

D-34

Mean NSM hydroperiod matches for WCA-1 for the 31 yr. simulation



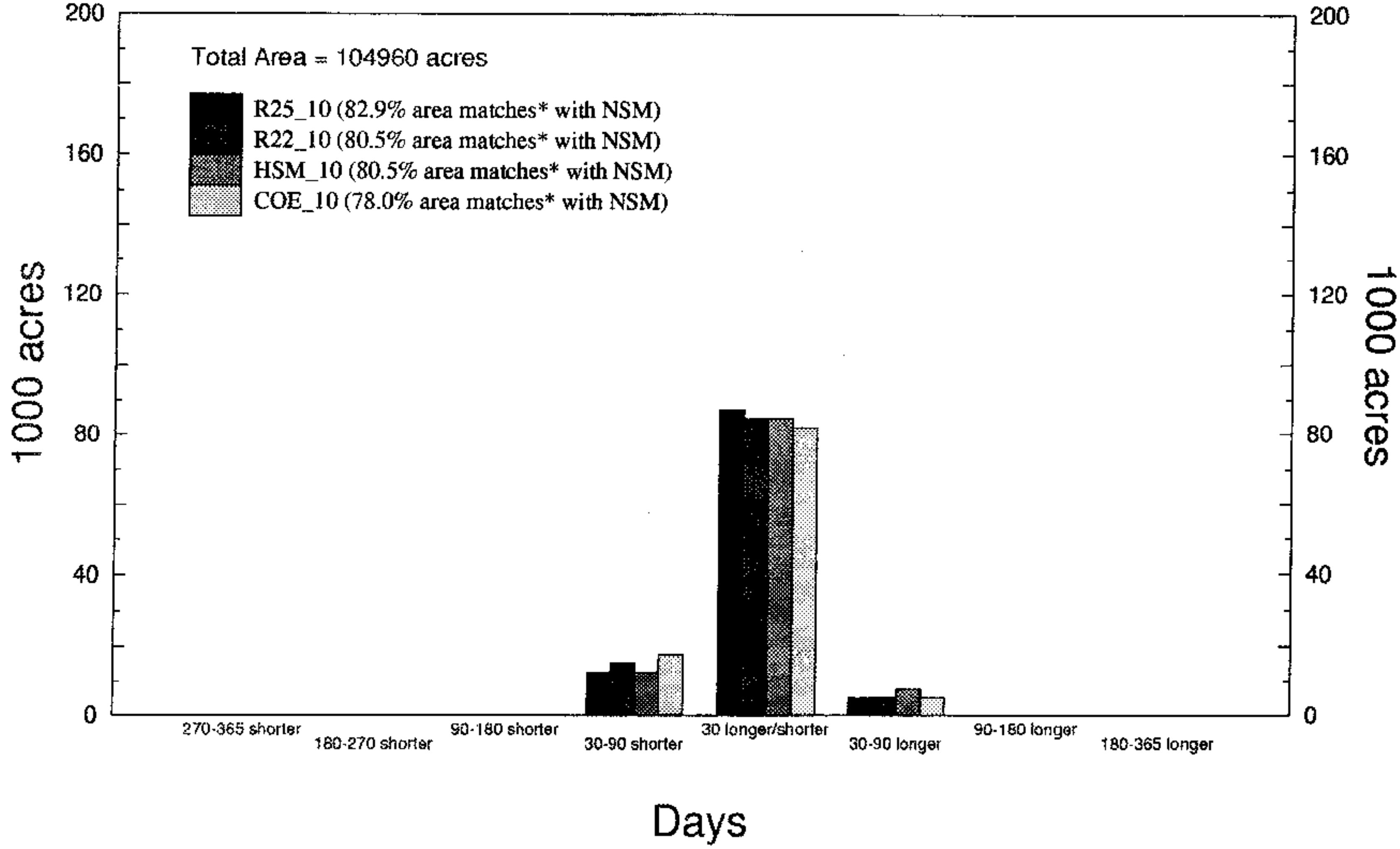
D-40

Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wed Apr 30 14:33:37 1997

SFWMM Simulation

Mean NSM hydroperiod matches for WCA-2A for the 31 yr. simulation

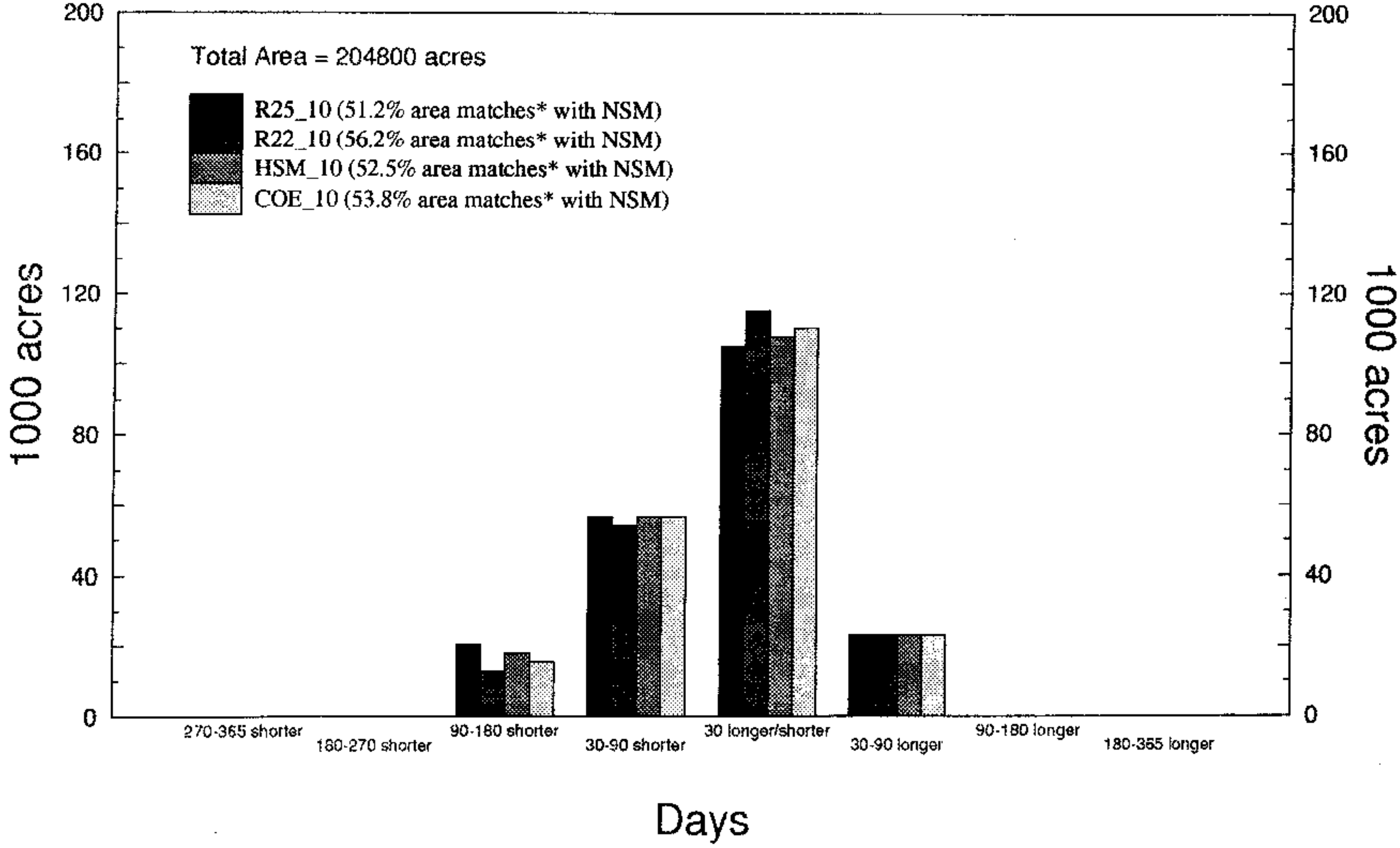


Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wed Apr 30 14:33:46 1997

SFWMM Simulation

Mean NSM hydroperiod matches for WCA-3A(North) for the 31 yr. simulation



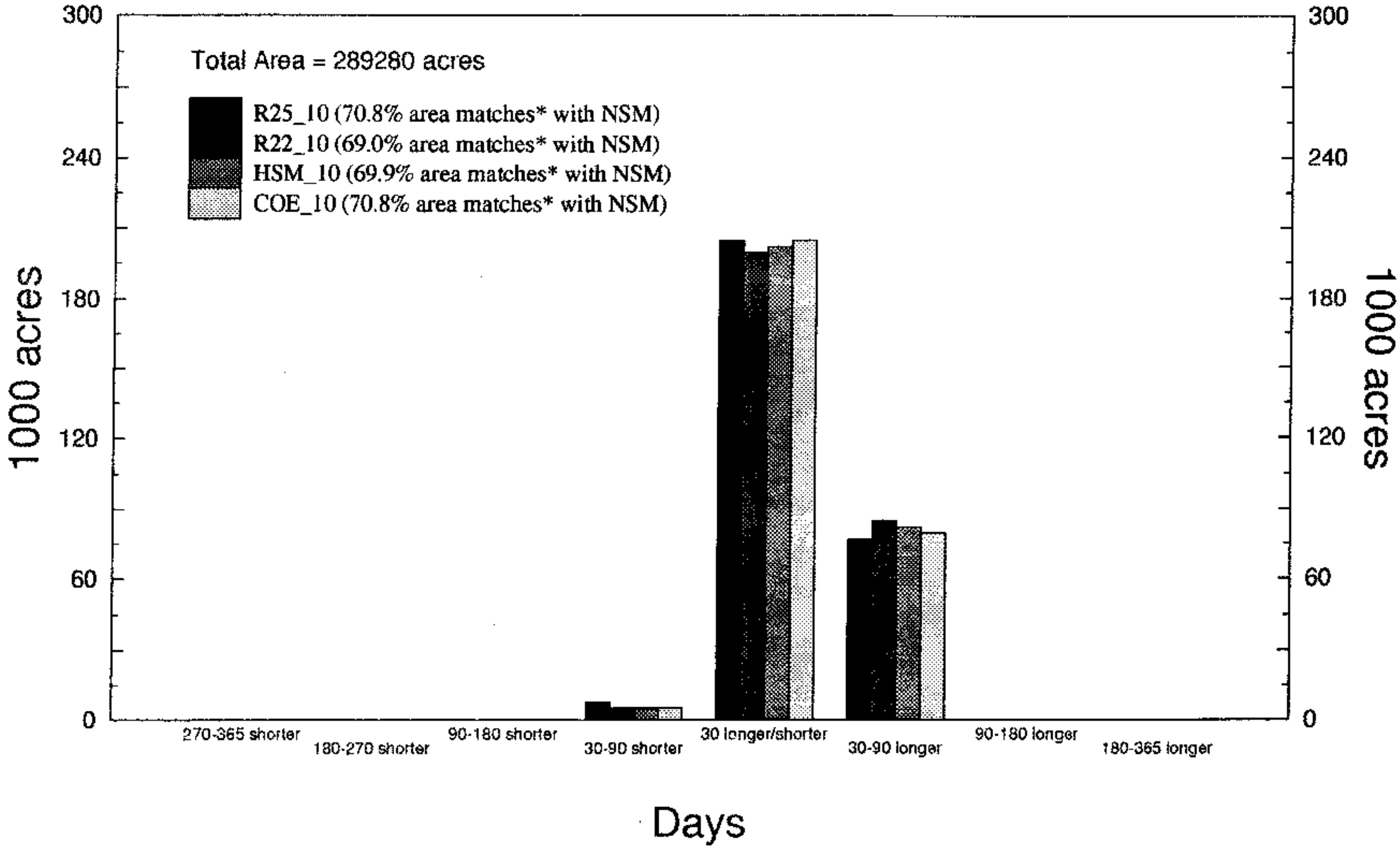
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wed Apr 30 14:33:56 1997

SFWMM Simulation

D-42

Mean NSM hydroperiod matches for WCA-3A(South) for the 31 yr. simulation



D-43

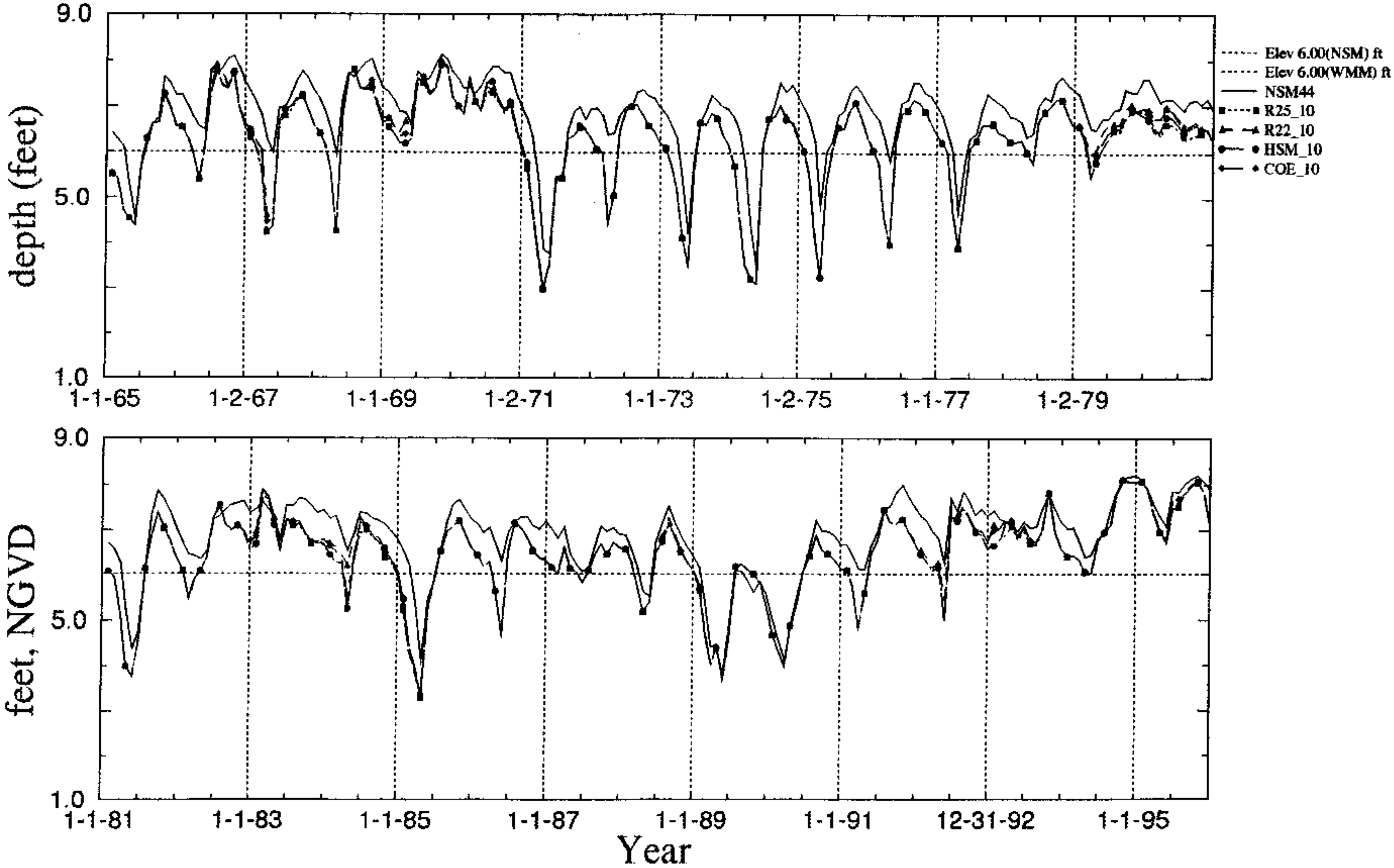
Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wed Apr 30 14:34:09 1997

SFWMM Simulation

Performance Measures for
Everglades National Park

Stage Hydrograph for Marl Lands in NW SRS
Gage G-620, ENP, Cell R19 C18

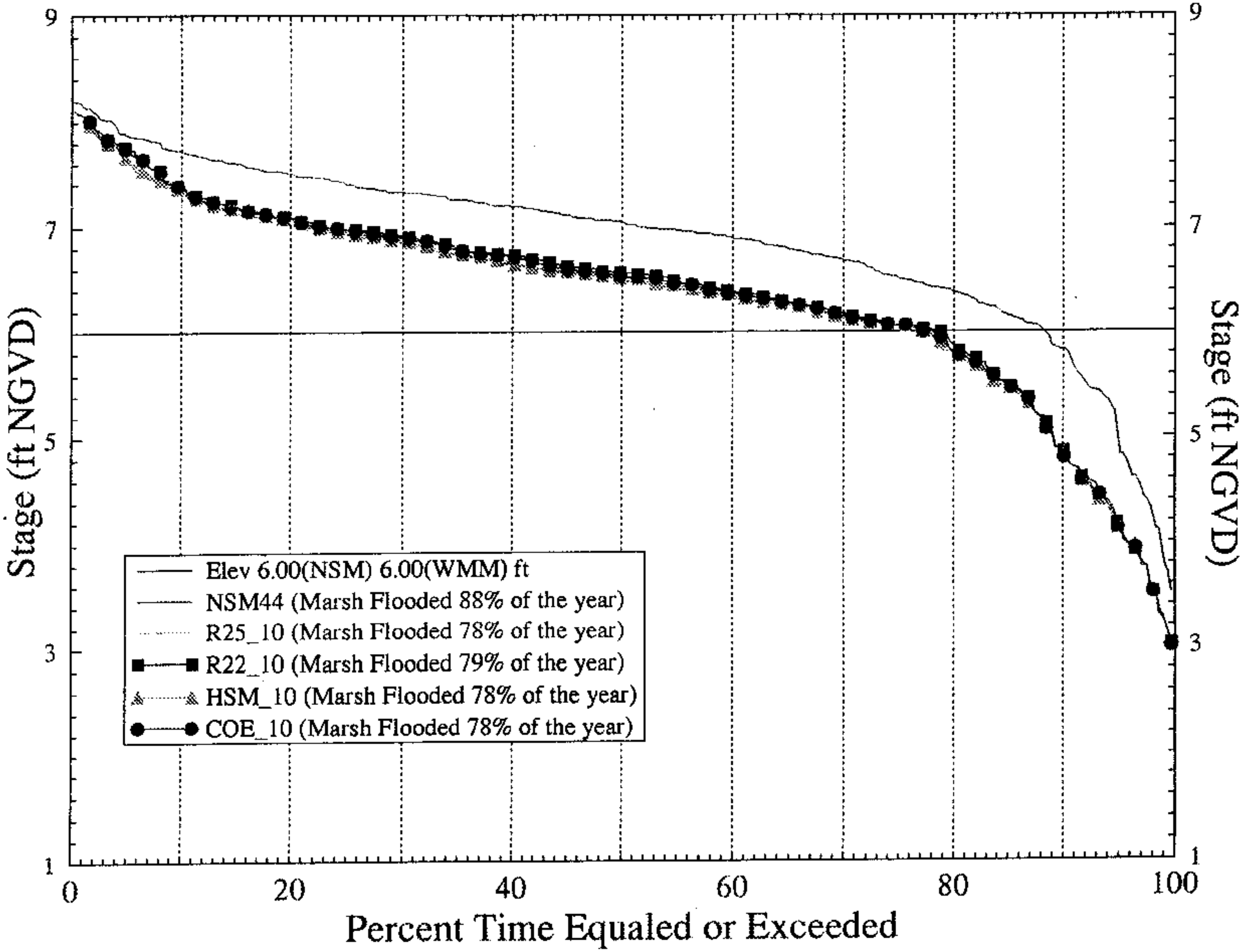


D-45

Wed Apr 30 12:43:51 1997

Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves for Marl Lands in NW SRS
Gage G-620, ENP, Cell R19 C18

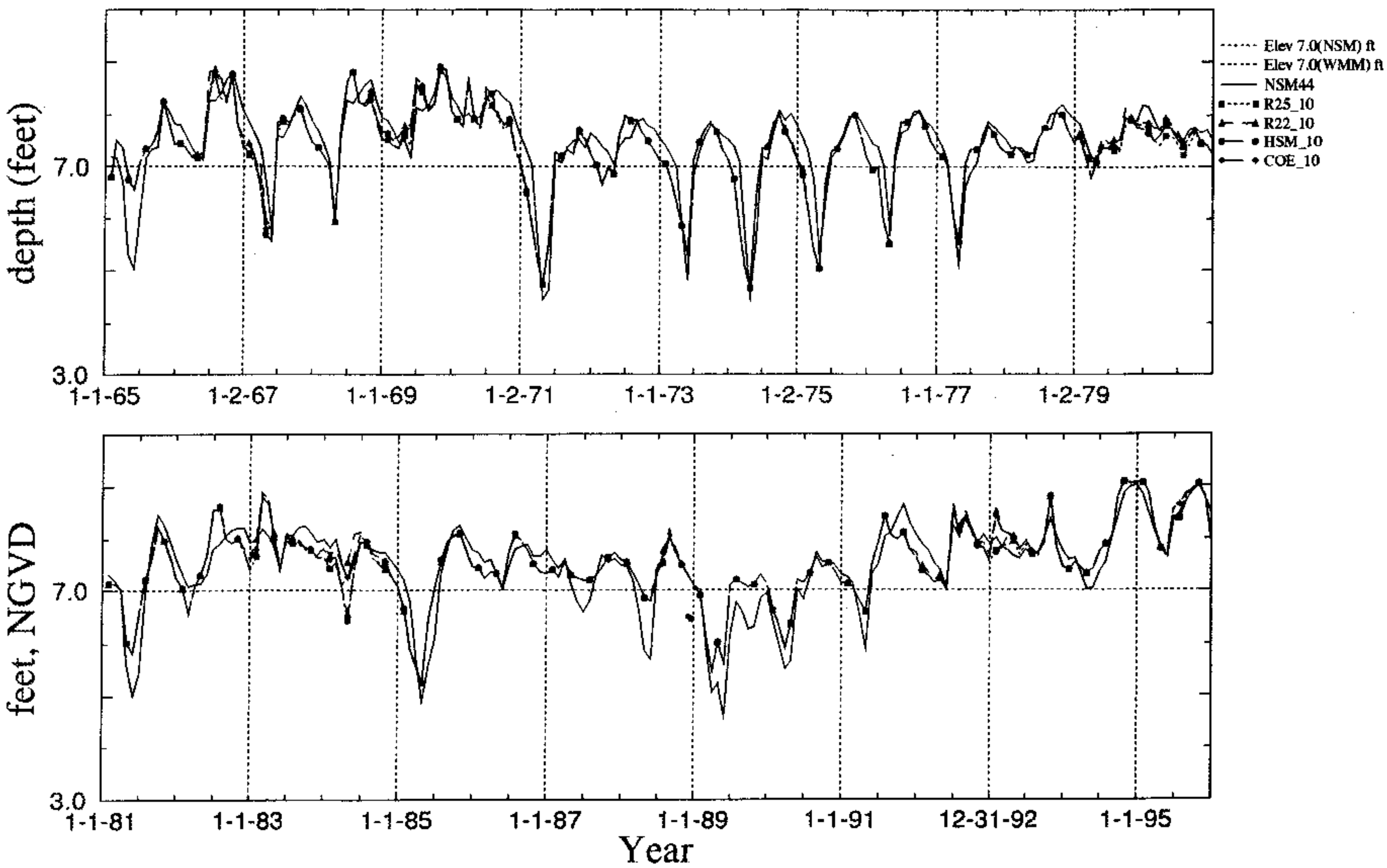


D-46

Wed Apr 30 12:42:08 1997

Environmental, Level II, ENP
SFWMM Simulation

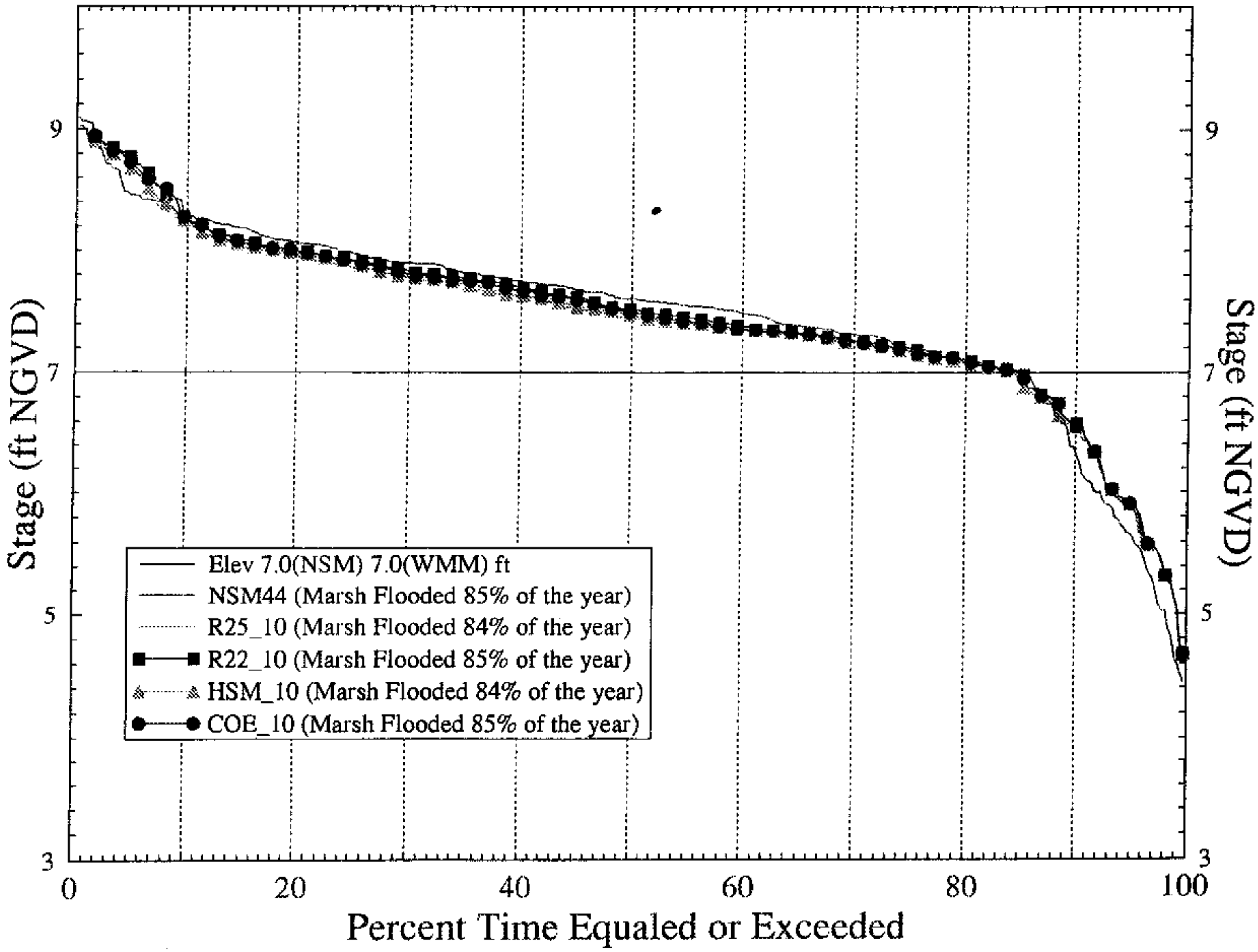
Stage Hydrograph at Northern Shark River Slough
Gage NP-201, Cell R21 C19



Wed Apr 30 12:44:16 1997

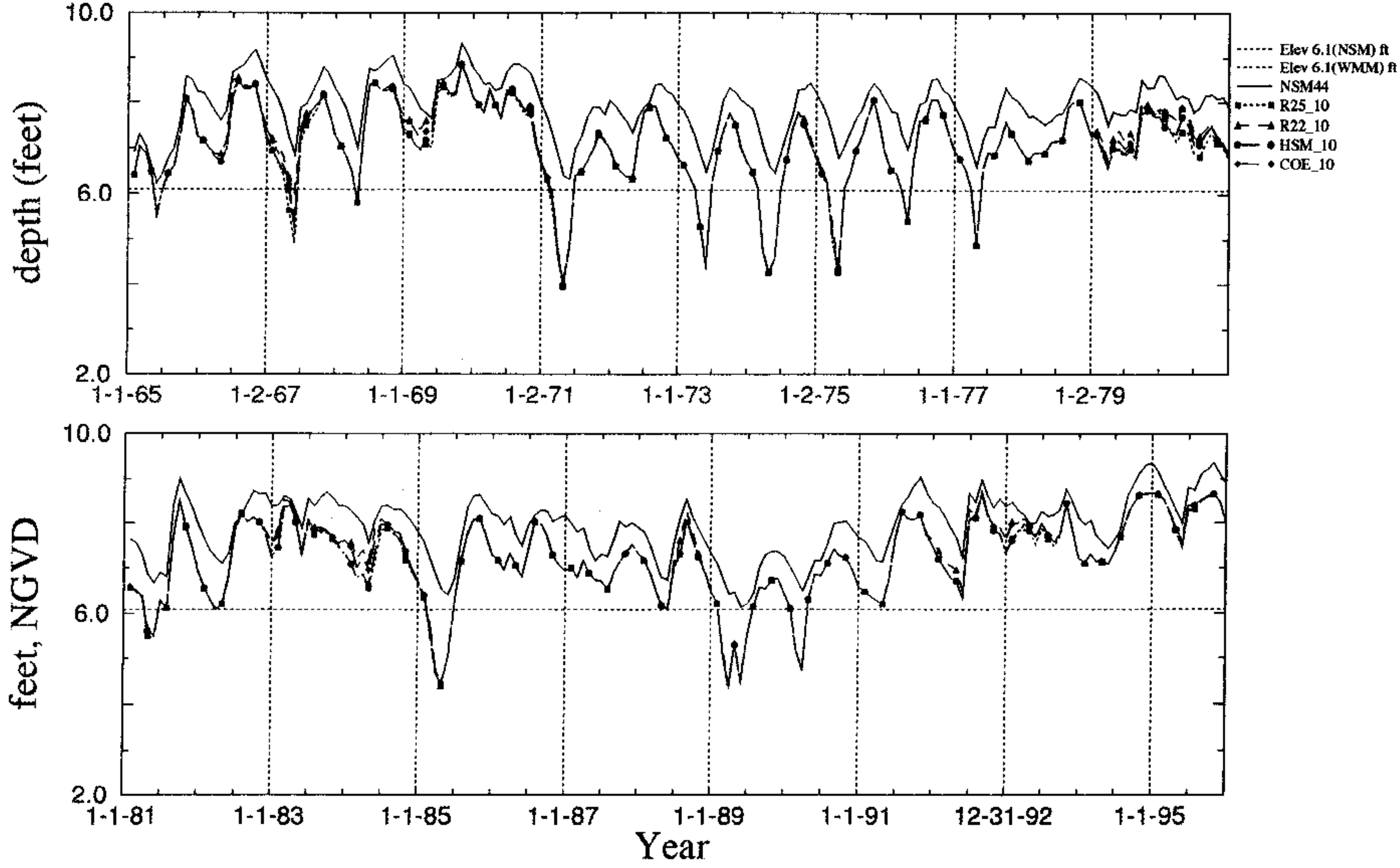
Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at Northern Shark River Slough
Gage NP-201, Cell R21 C19



D-48

Stage Hydrograph at N.E. Shark River Slough
Gage NESRS-2, Cell R21 C24

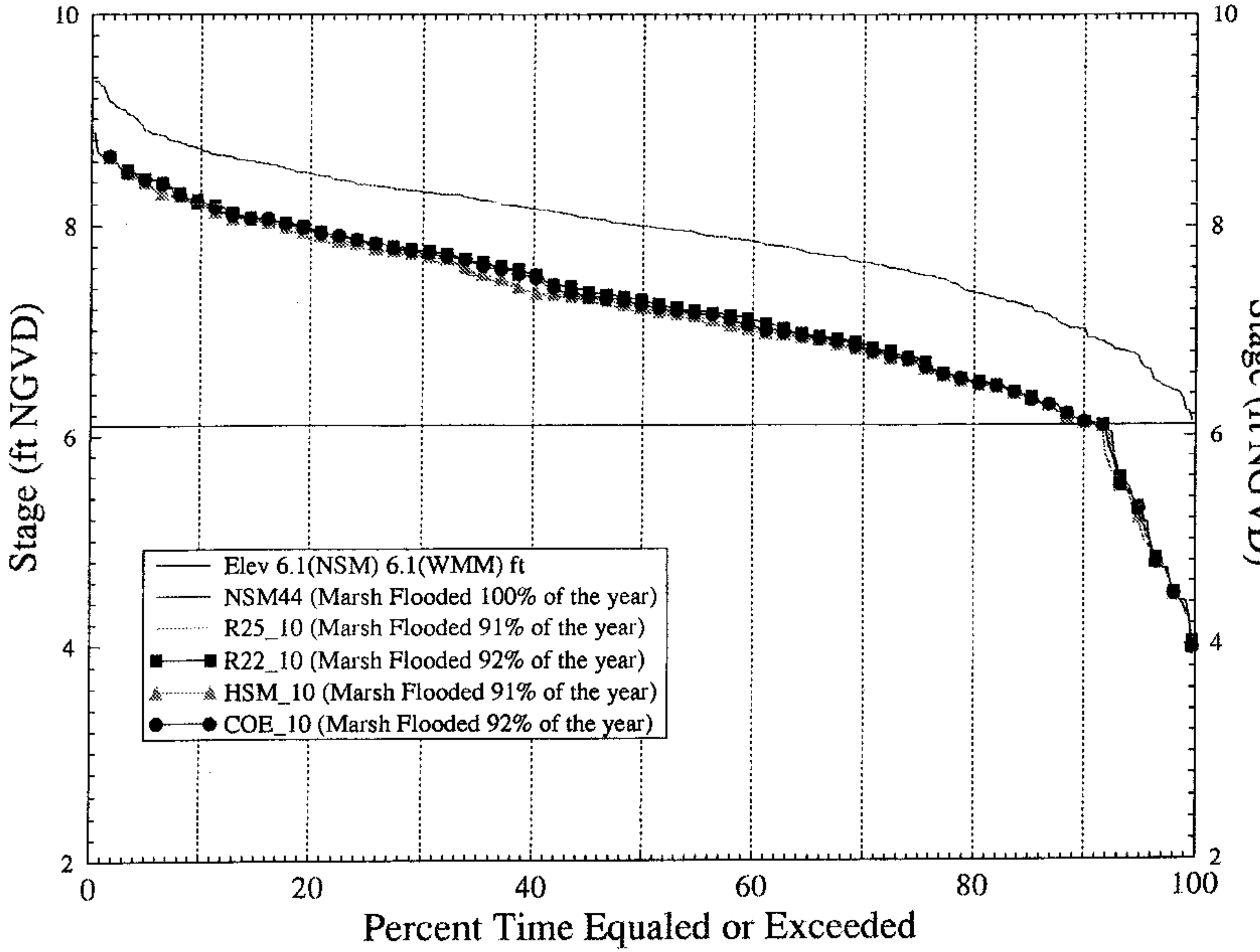


b-49

Wed Apr 30 12:44:02 1997

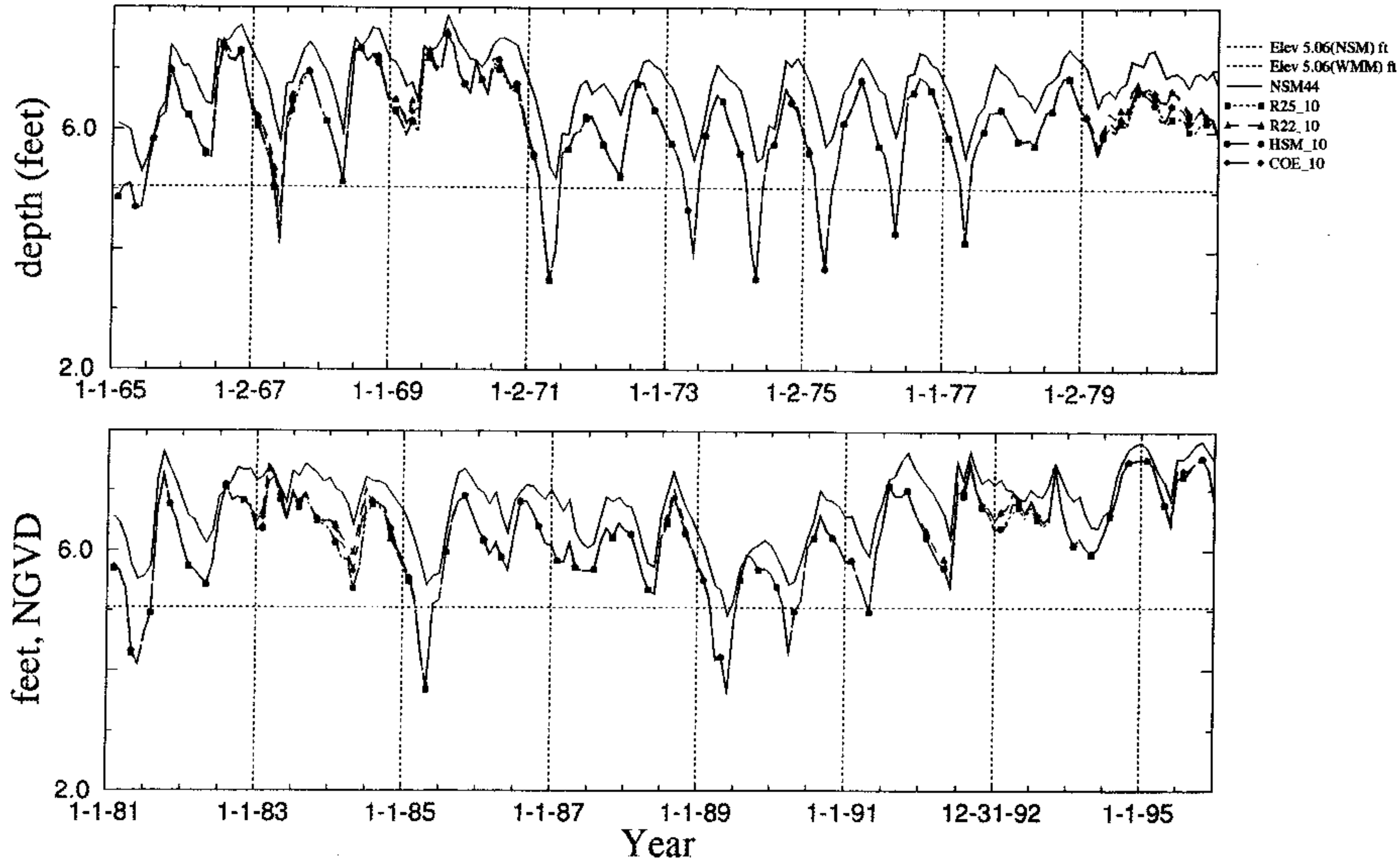
Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at N.E. Shark River Slough
Gage NESRS-2, Cell R21 C24



D-50

Stage Hydrograph at Everglades National Park
Gage NP-33, Cell R17 C20

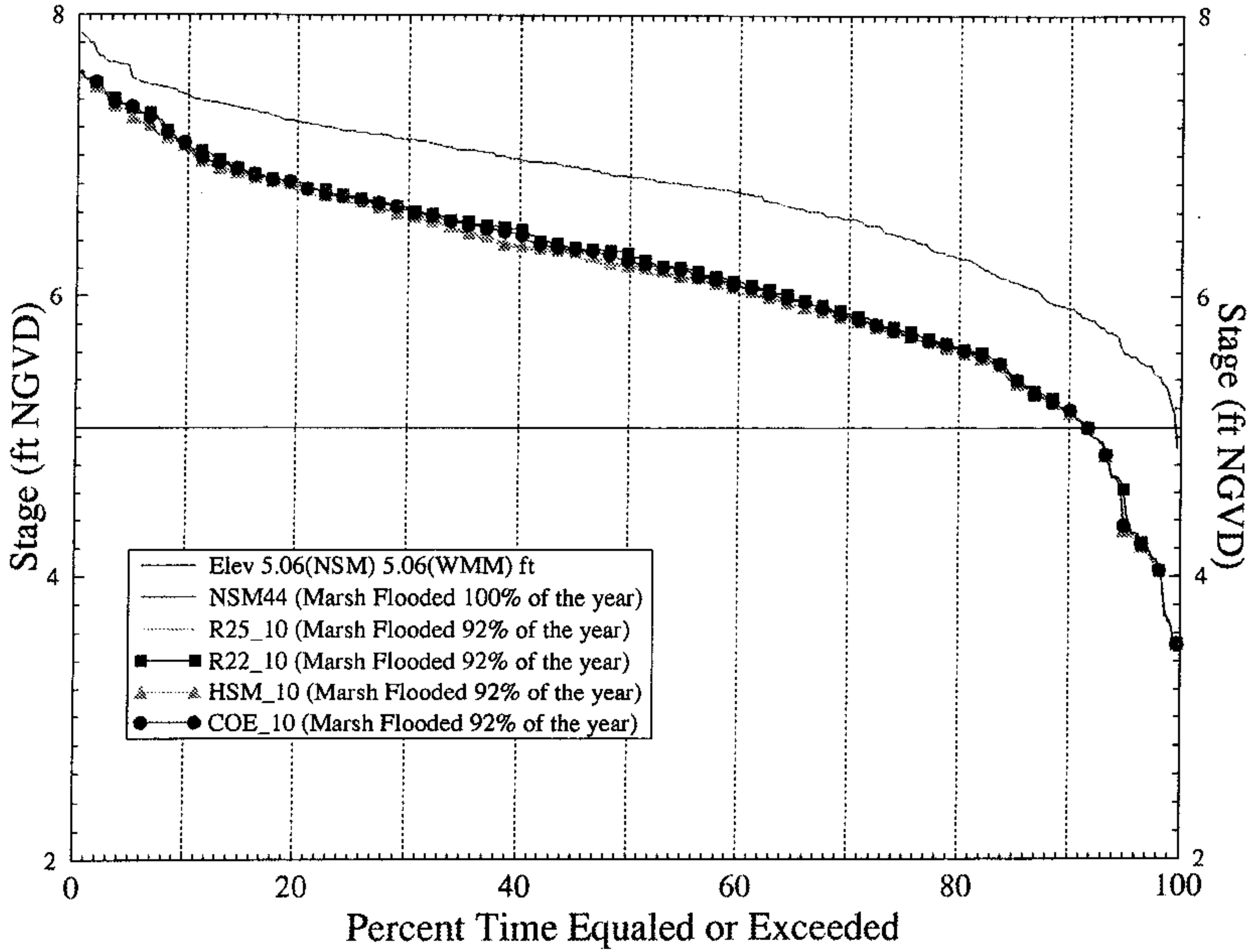


D-51

Wed Apr 30 12:44:27 1997

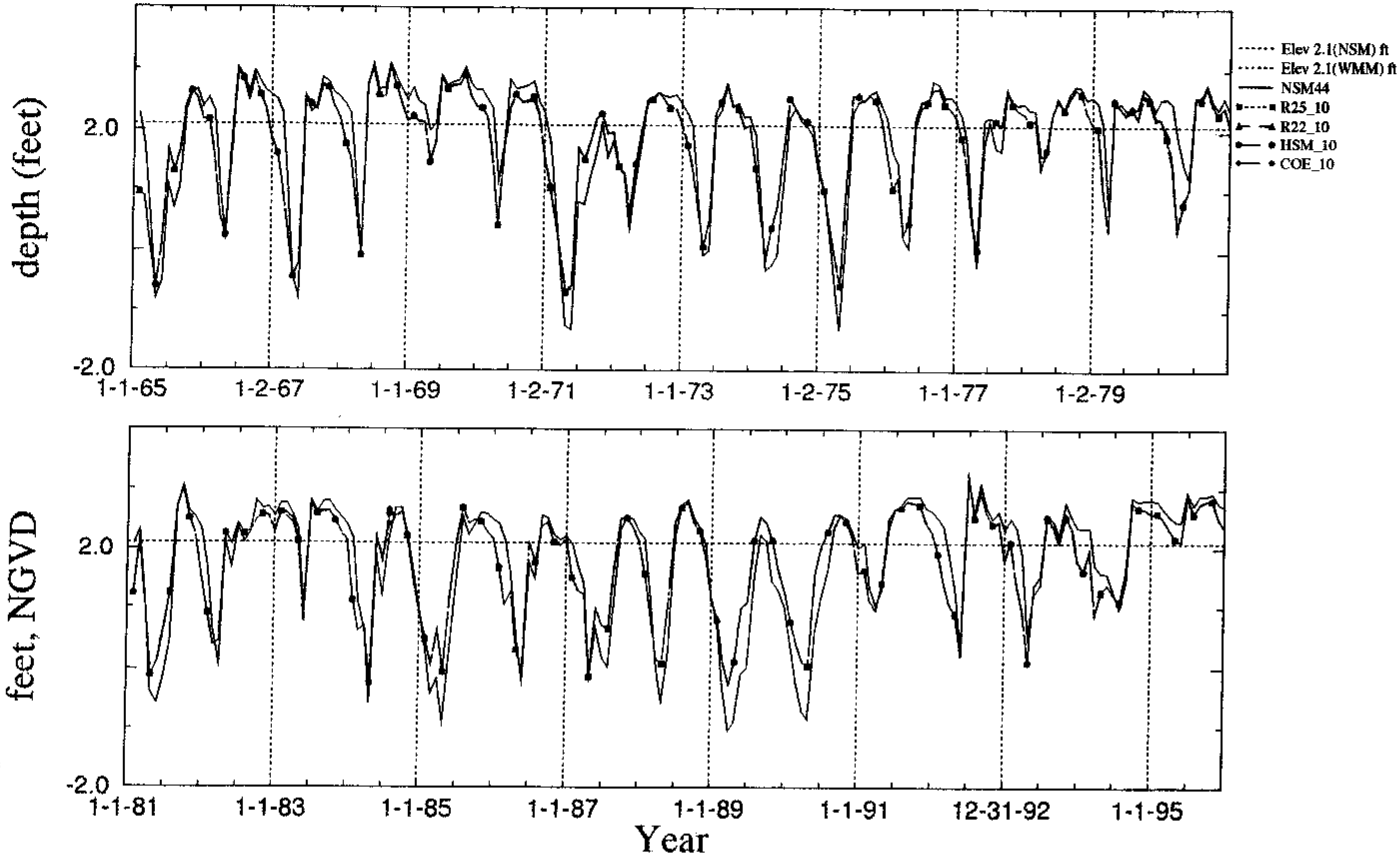
Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at Everglades National Park
Gage NP-33, Cell R17 C20



D-52

Stage Hydrograph at C-111 Basin
Gage G-1251, Cell R7 C24

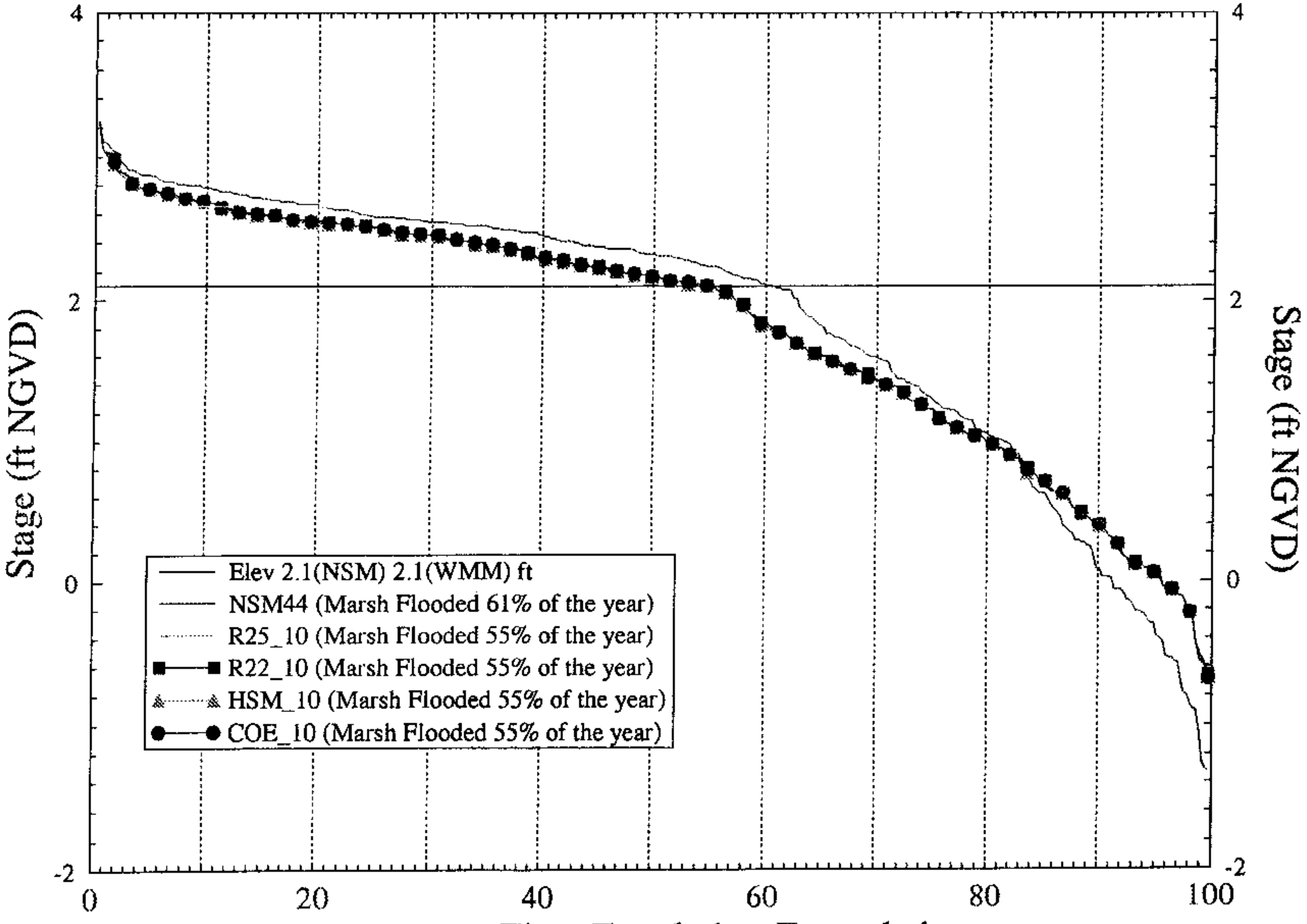


C5-4

Wed Apr 30 12:43:38 1997

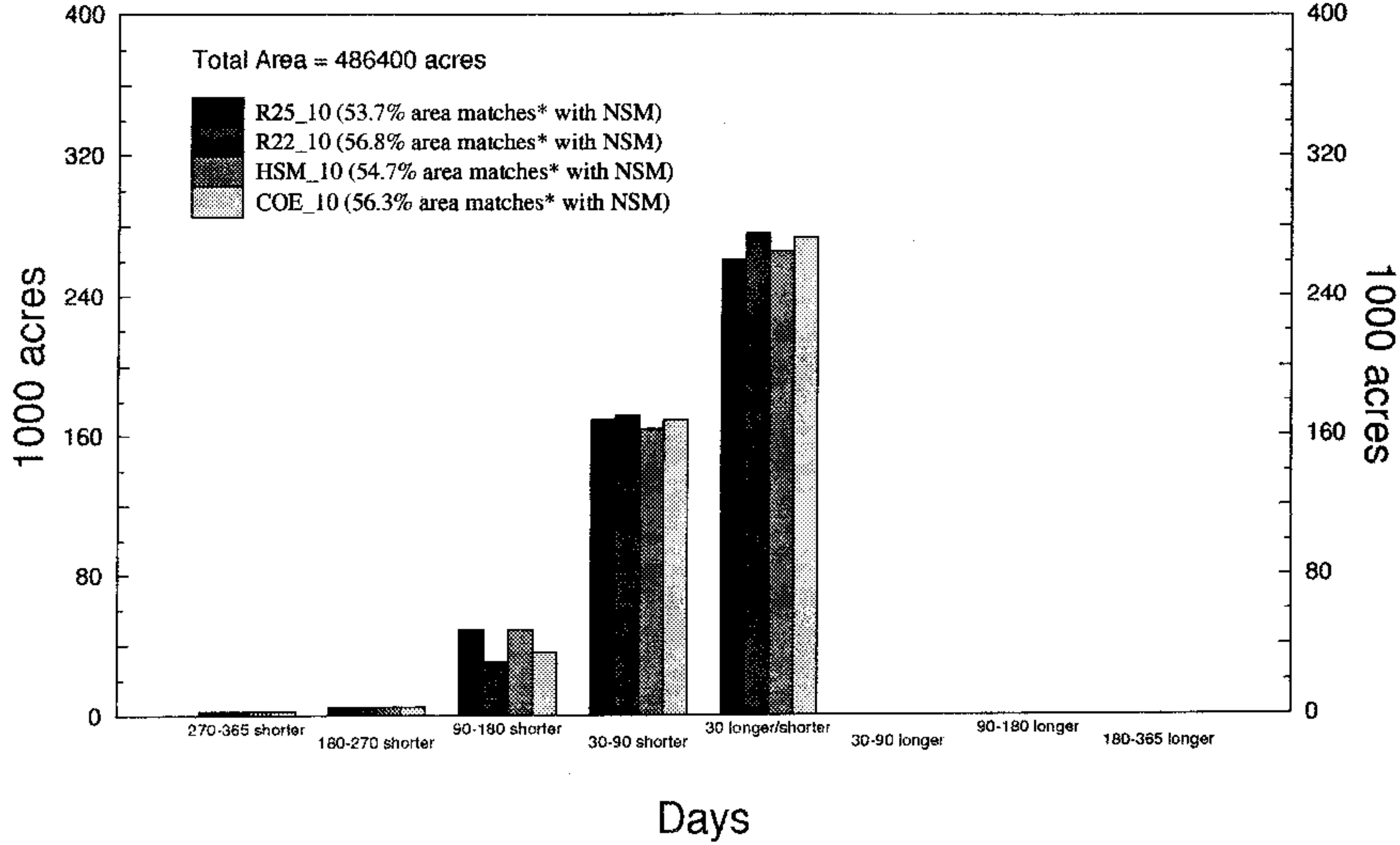
Environmental/WCA/ENP
SFWMM Simulation

Stage Duration Curves at C-111 Basin
Gage G-1251, Cell R7 C24



D-54

Mean NSM hydroperiod matches for the Everglades National Park for the 31 yr. simulation

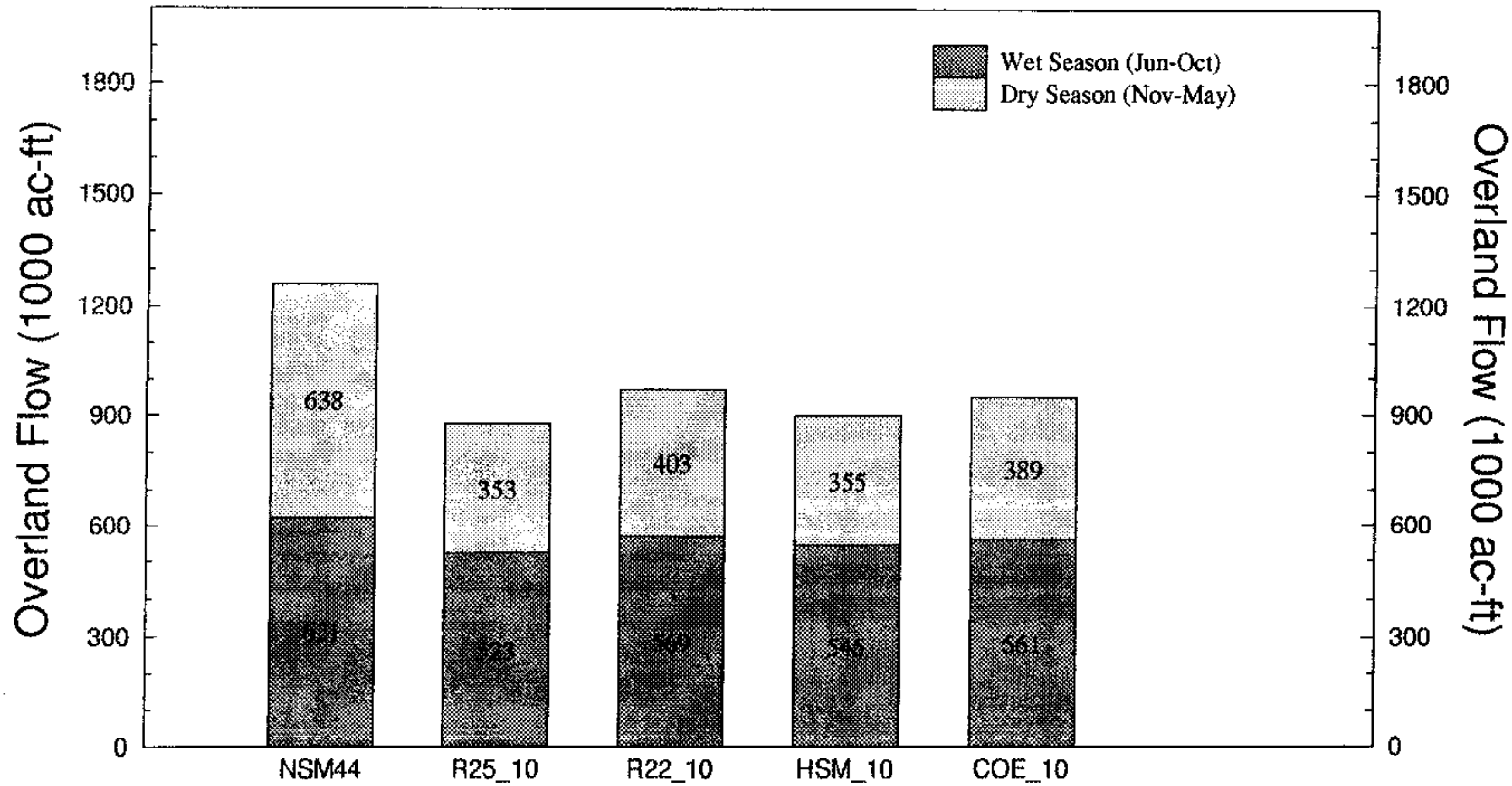


Note: xaxis represents hydroperiod days shorter or longer as compared to NSMv4.3
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Wed Apr 30 14:40:53 1997

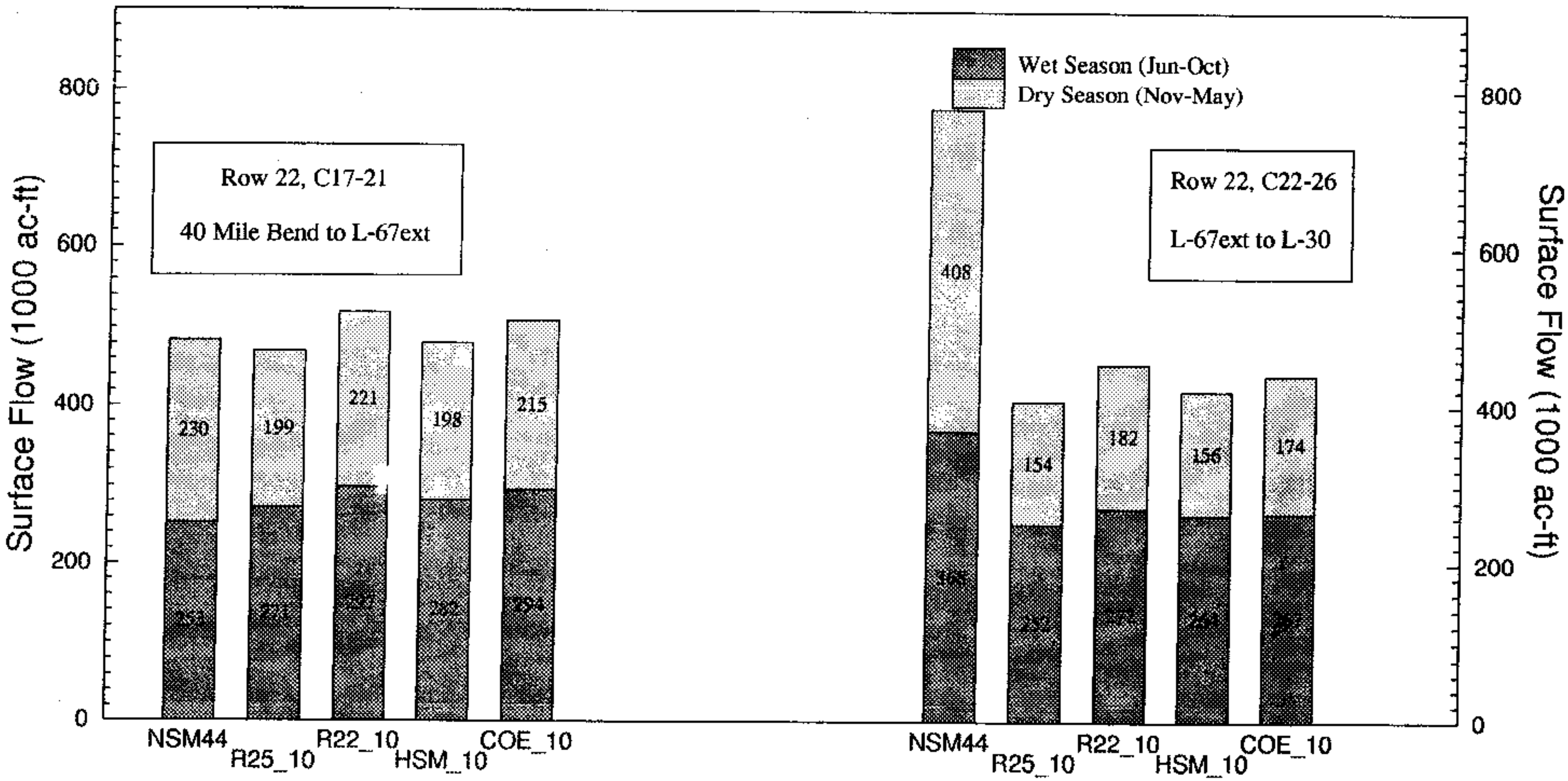
SFWMM Simulation

Wet/Dry Season Average Overland Flows South of Tamiami Trail to ENP for the 31 yr. simulation



Note: Flow represents overland flows for cells Row 22 Columns 17 thru 26. NSM water depths at key ENP gage locations are used as operational targets for most alternatives. NSM flows are NOT targets (except for ALT #4) and are shown for comparative purposes only. Environmental, Level I, ENP

Average Annual Overland Flows to ENP South of Tamiami Trail, West & East of L-67ext for the 31 year simulation period



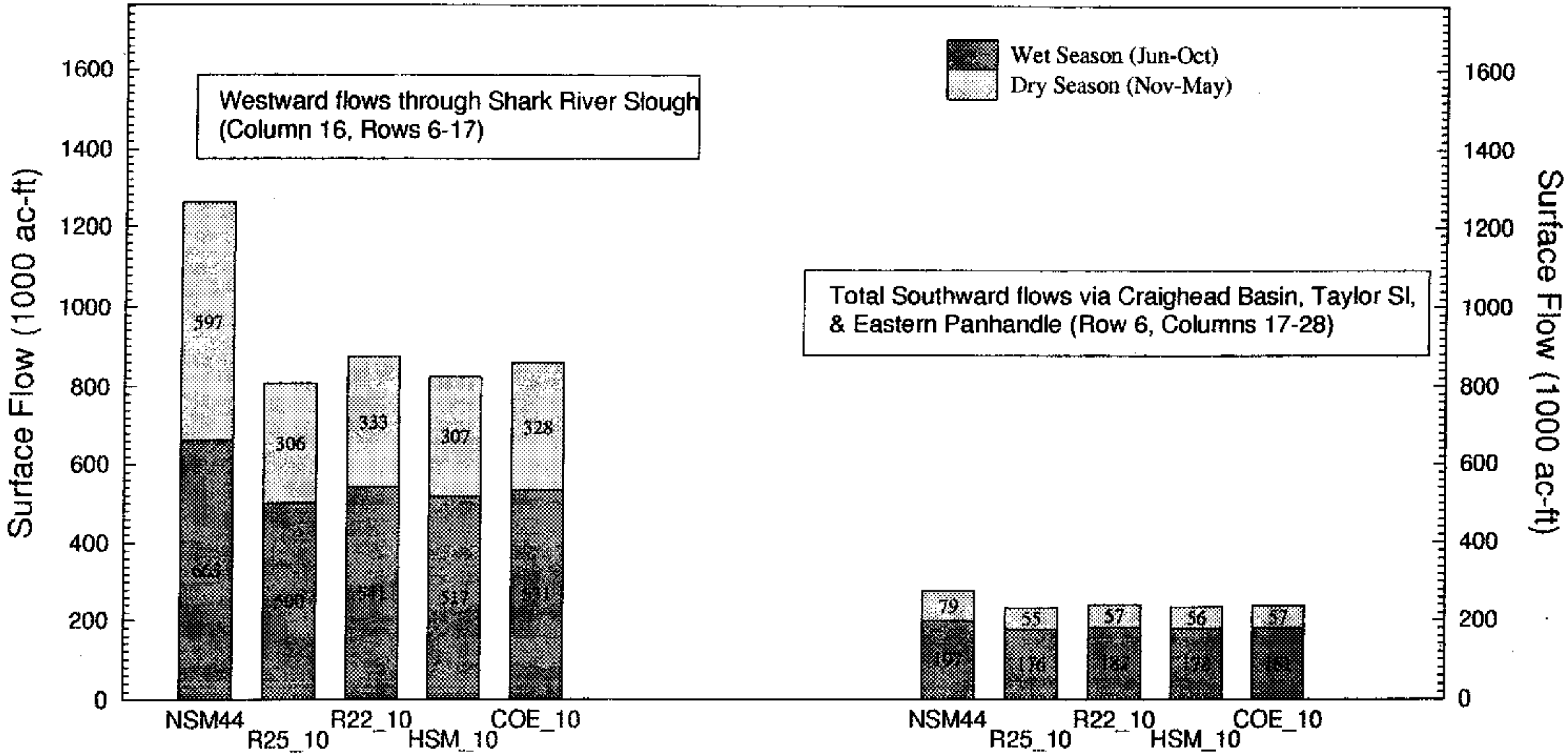
D-57

Note: Flow represents overland flows for cells Row 22 Columns 22 thru 26. NSM water depths at key ENP gage locations are used as operational targets for most alternatives. NSM flows are NOT targets (except for ALT #4) and are shown for comparative purposes only.

Wed Apr 30 14:42:27 1997

Environmental, Level I, ENP
SFWMM Simulation

Average Annual Overland Flows toward Whitewater Bay and Florida Bay for the 31 year simulation period



8-58

Note: NSM water depths at key ENP gage locations are used as operational targets for most alternatives.
NSM flows are NOT targets and are shown for comparative purposes only.

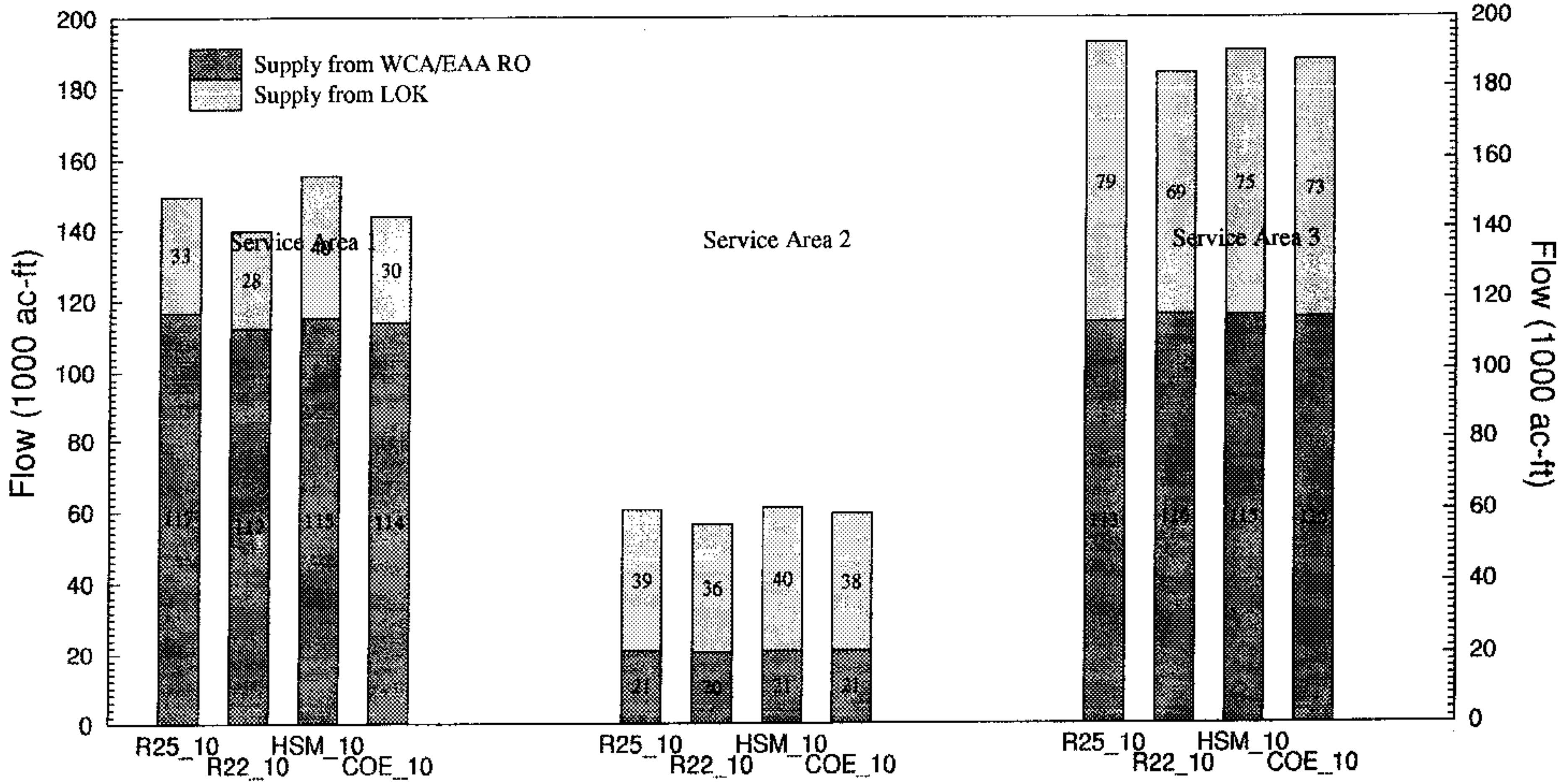
Wed Apr 30 14:43:06 1997

Environmental, Level I, ENP

Performance Measures for the

Lower East Coast Service Areas

Mean Annual Regional System Water Supply Deliveries to LEC Service Areas for the five Drought years (71,75,81,85,89)



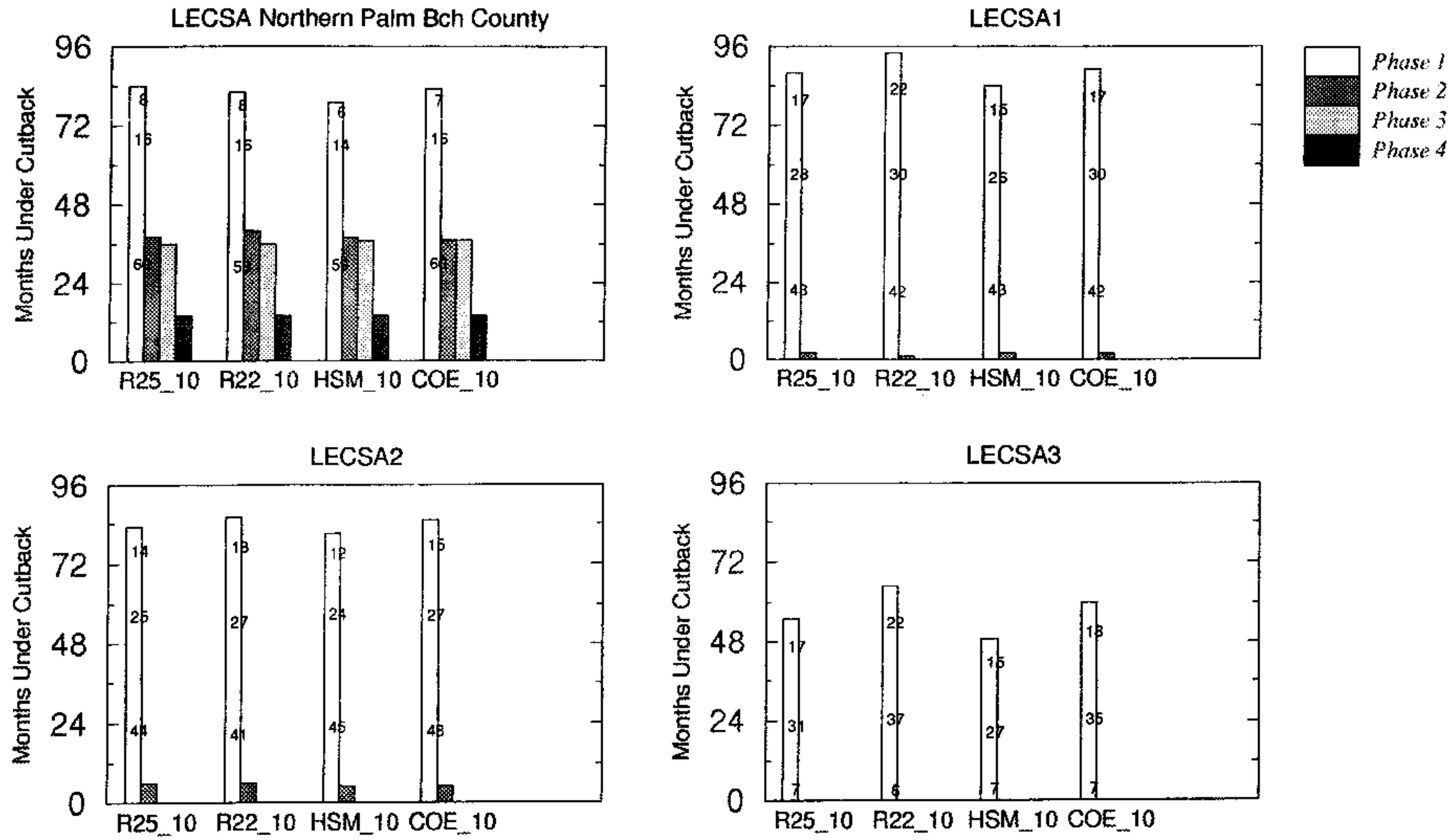
Note: Structure flows included: SA1=S39+LWDD+ADDSLW+ACMEWS+WSL8S; SA2=S38+S34; SA3=S31+S334+S337
Supply RECEIVED from LOK may be less than what is DELIVERED at LOK due to conveyance constraints.

Wed Apr 30 14:46:46 1997

Water Supply, Level I, LECSA1/2/3
SFWMM Simulation

D-59

Number of Months of Simulated Water Supply Cutbacks
for the 1965 - 1995 Simulation Period



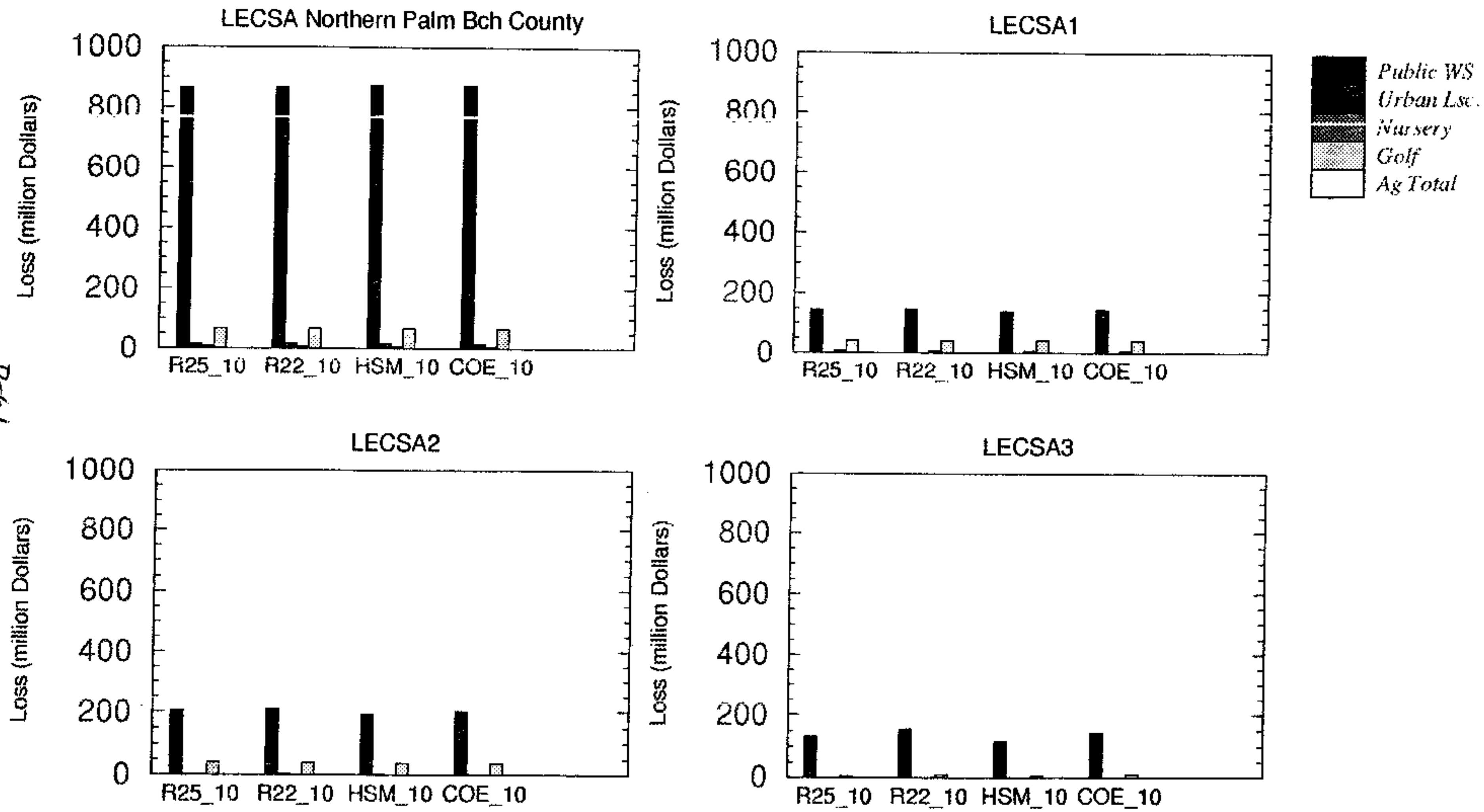
Note: Phase 1 water restrictions could be induced by a) Lake stage in Supply Side Management Zone (indicated by upper data label), b) Local Trigger well stages (lower data label), and c) Dry season criteria (indicated by middle data label).

D-60

Wed Apr 30 14:47:01 1997

Water Supply, Level I, LECSA-NPB/1/2/3

Total Water Shortage Impacts (Losses) for the 26 year Simulation Period



D-61

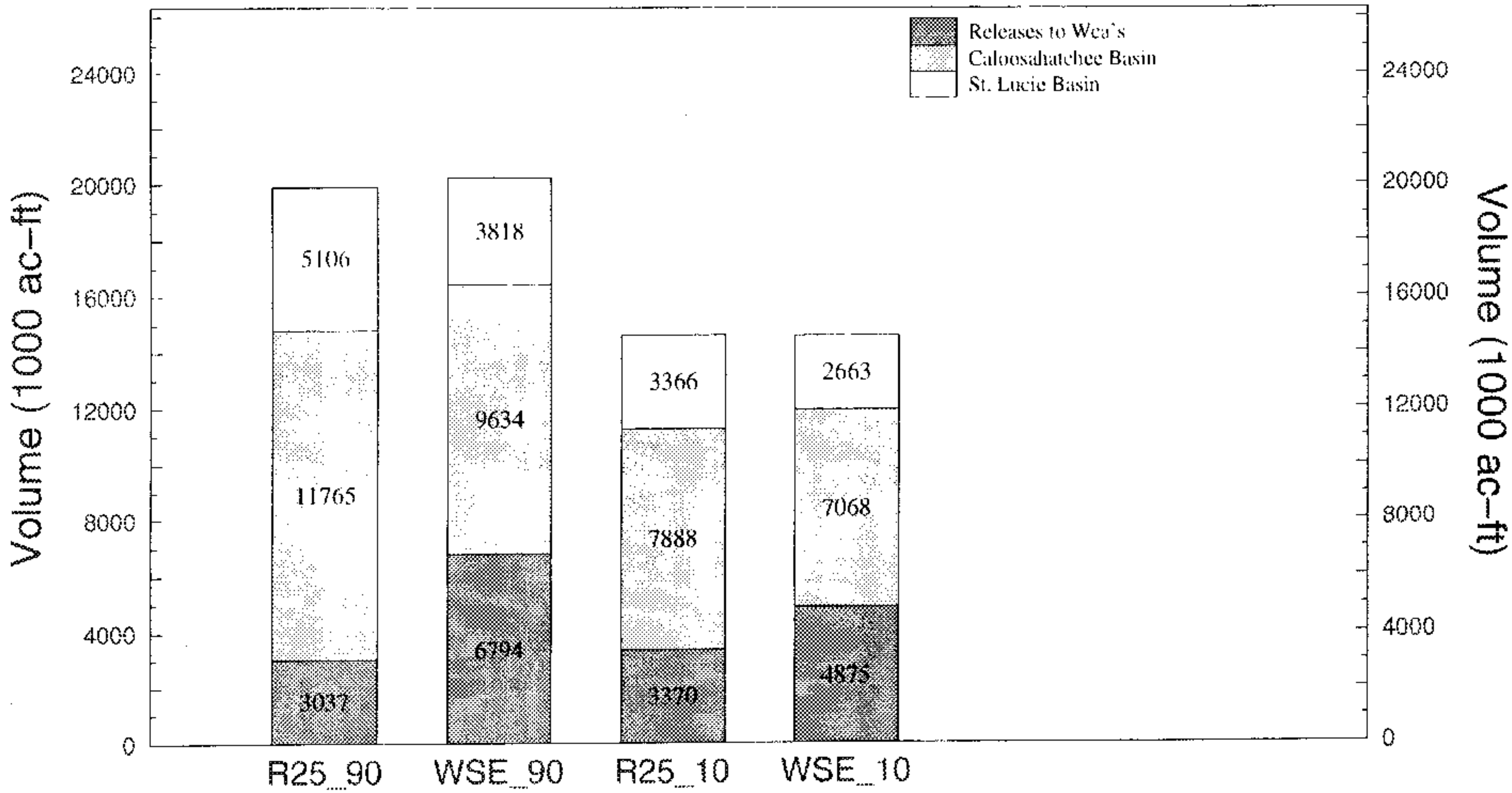
Wed Apr 30 14:47:44 1997

Water Supply, Level I, LECSA-NPB/1/2/3
SFWMM Simulation

APPENDIX E. WSE Simulations for 1990 & 2010 - Performance Measure Graphics

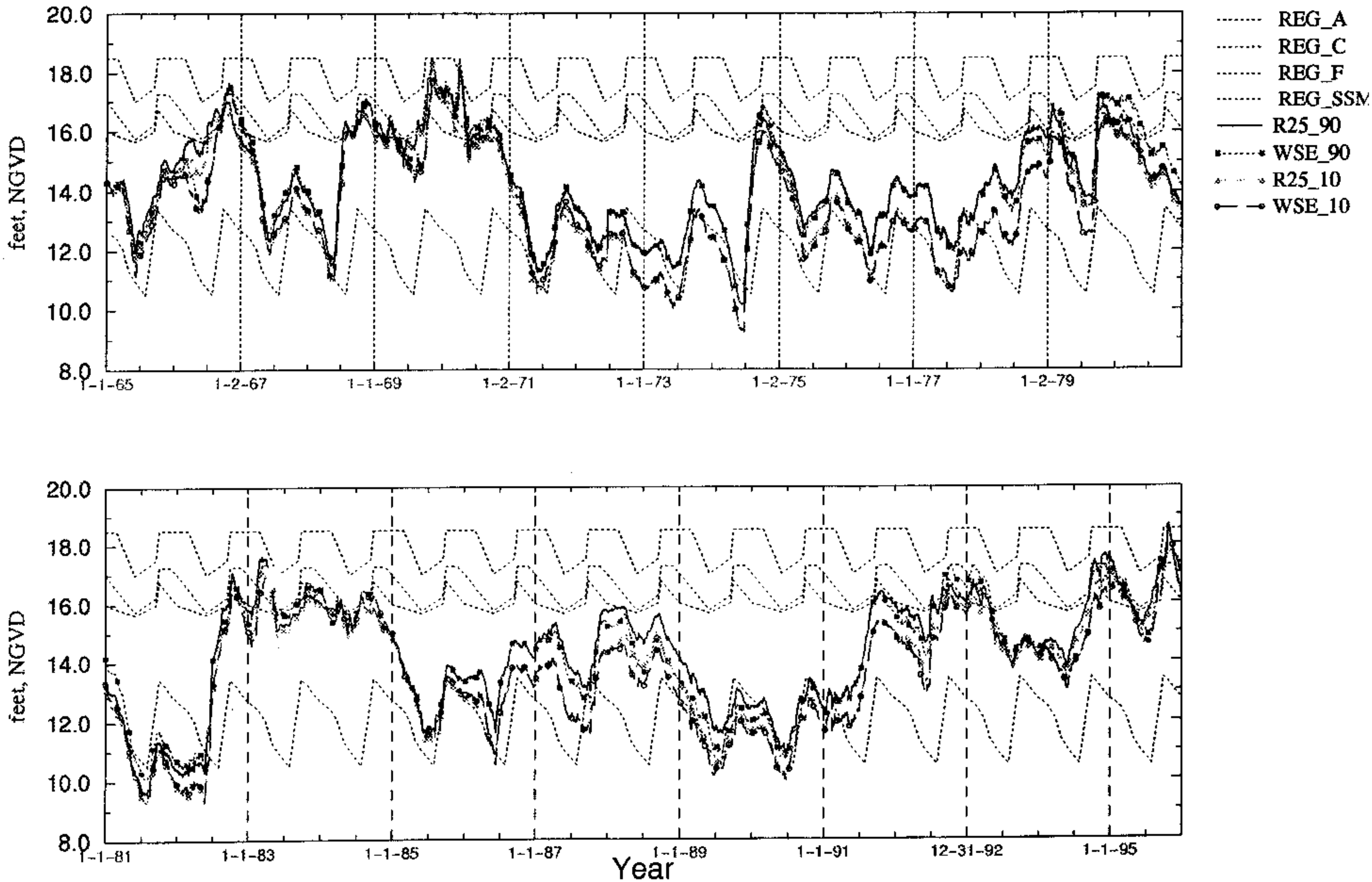
Performance Measures for
Lake Okeechobee

Total Flood Control Releases from Lake Okeechobee for the 31 yr (1965 – 1995) Simulation



Note: Although regulatory (flood control) discharges are summarized here in mean annual values, they do not occur every year. Typically they occur in 2–4 consecutive years and may not occur for up to 7 consecutive years.

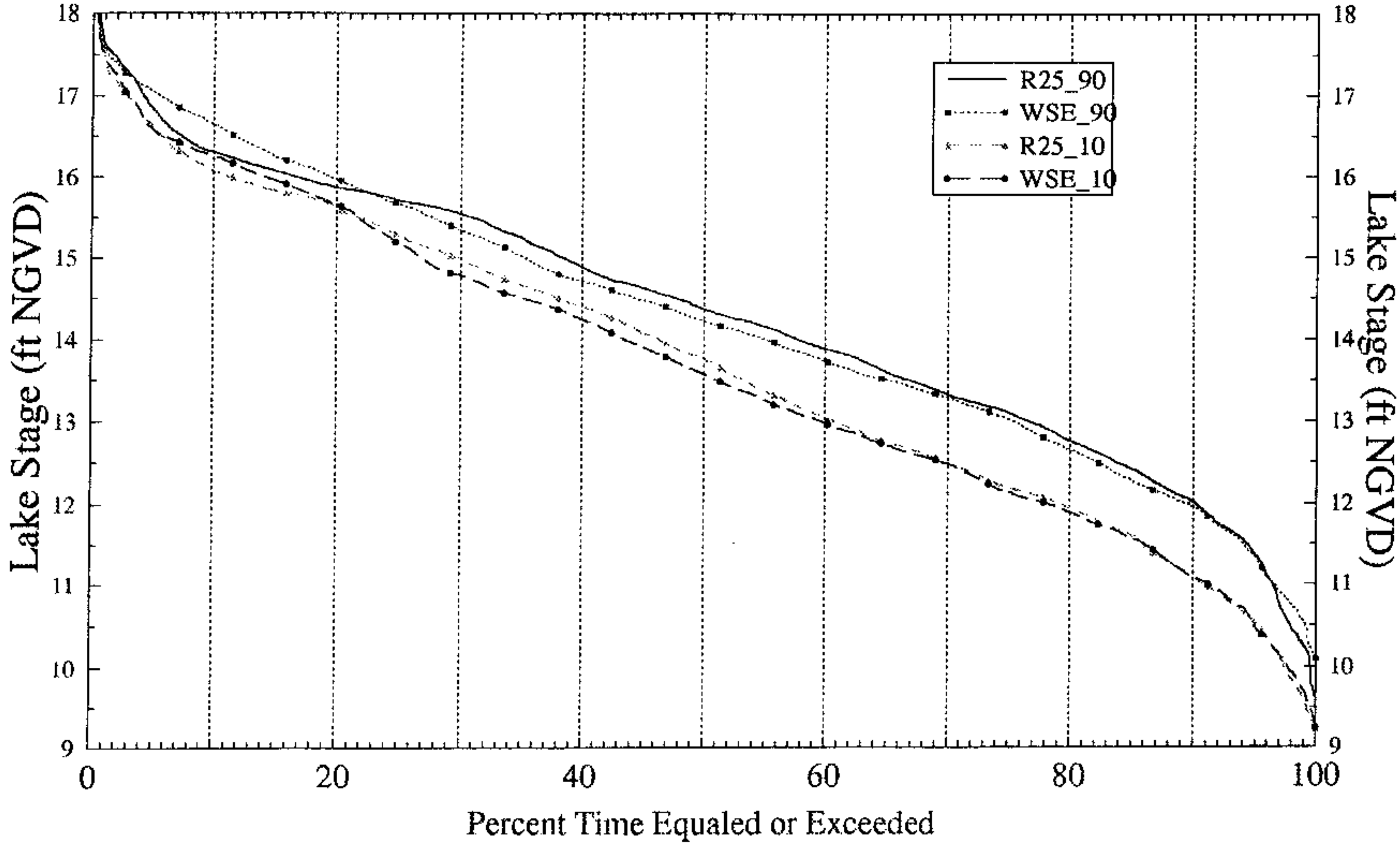
Daily Stage Hydrographs for Lake Okeechobee



Run date: 04/24/98 10:53:02
For Planning Purposes Only
SFWMM V3.2

E-3

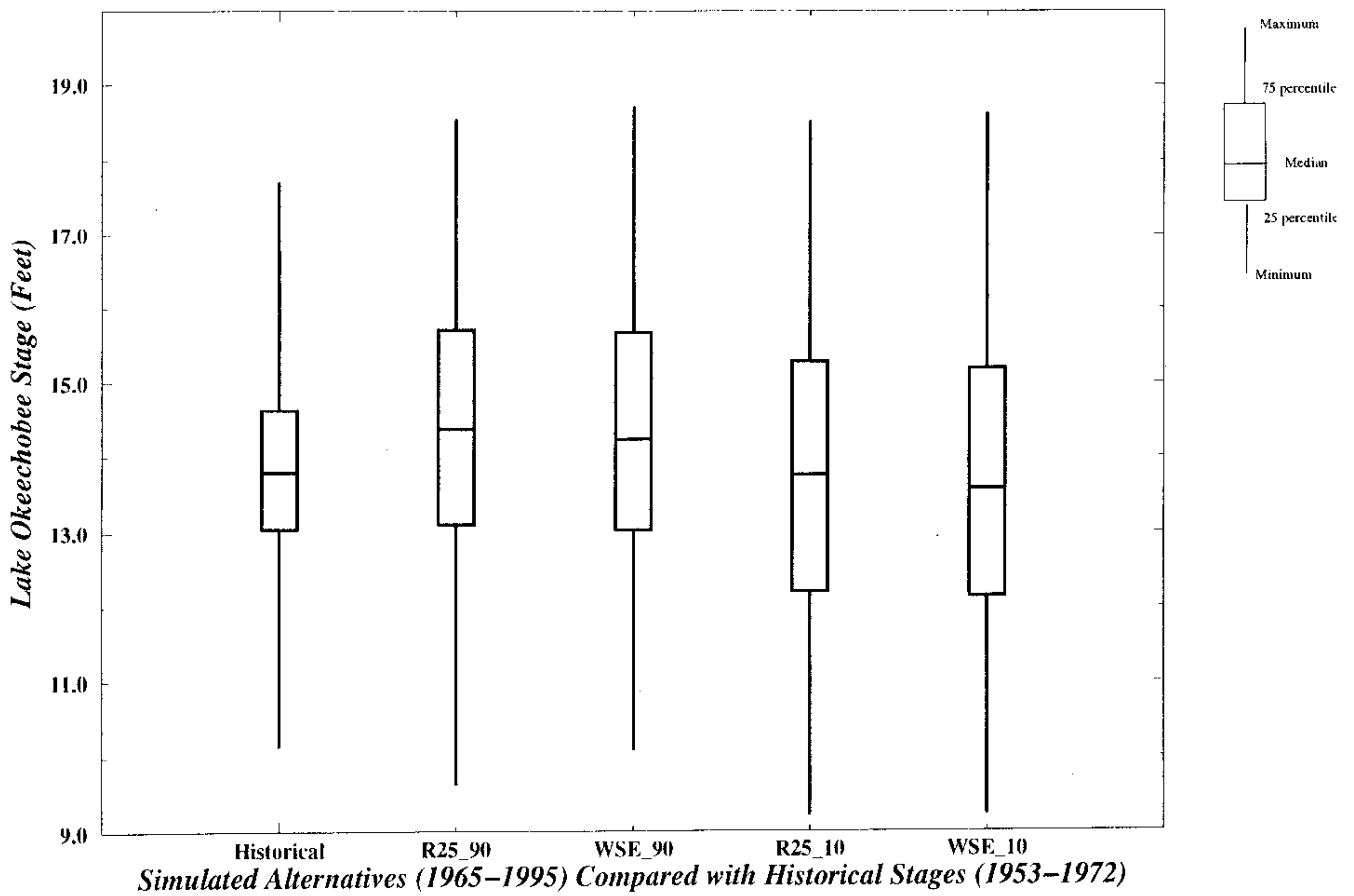
Lake Okeechobee Stage Duration Curves



Run date: 04/24/98 10:54:29
For Planning Purposes Only
SFWMM V3.2

E-4

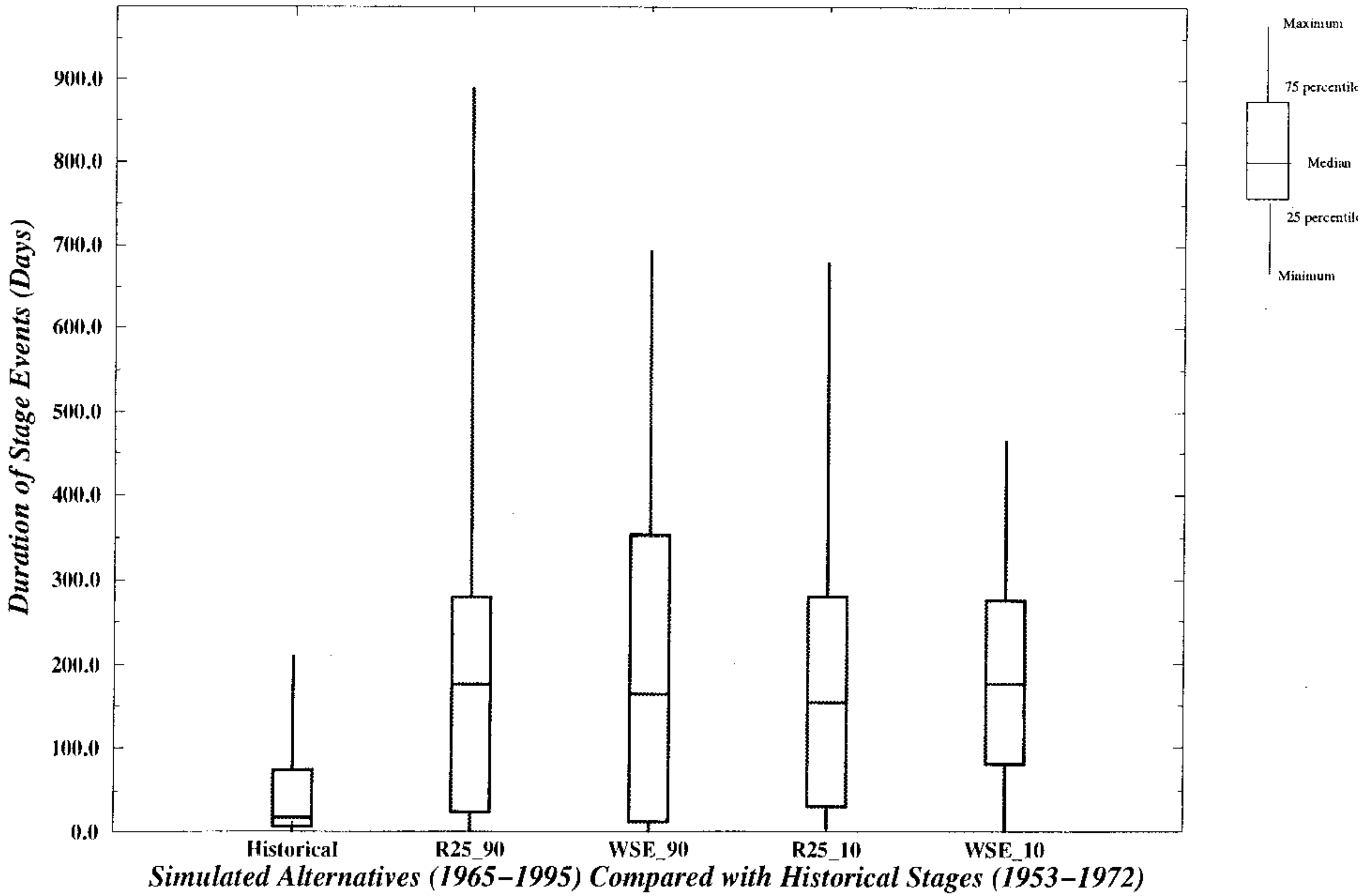
Lake Okeechobee Littoral Zone – Similarity in Lake Stages



Run date: 04/24/98 15:28:36
For Planning Purposes Only

Lake Okeechobee Littoral Zone

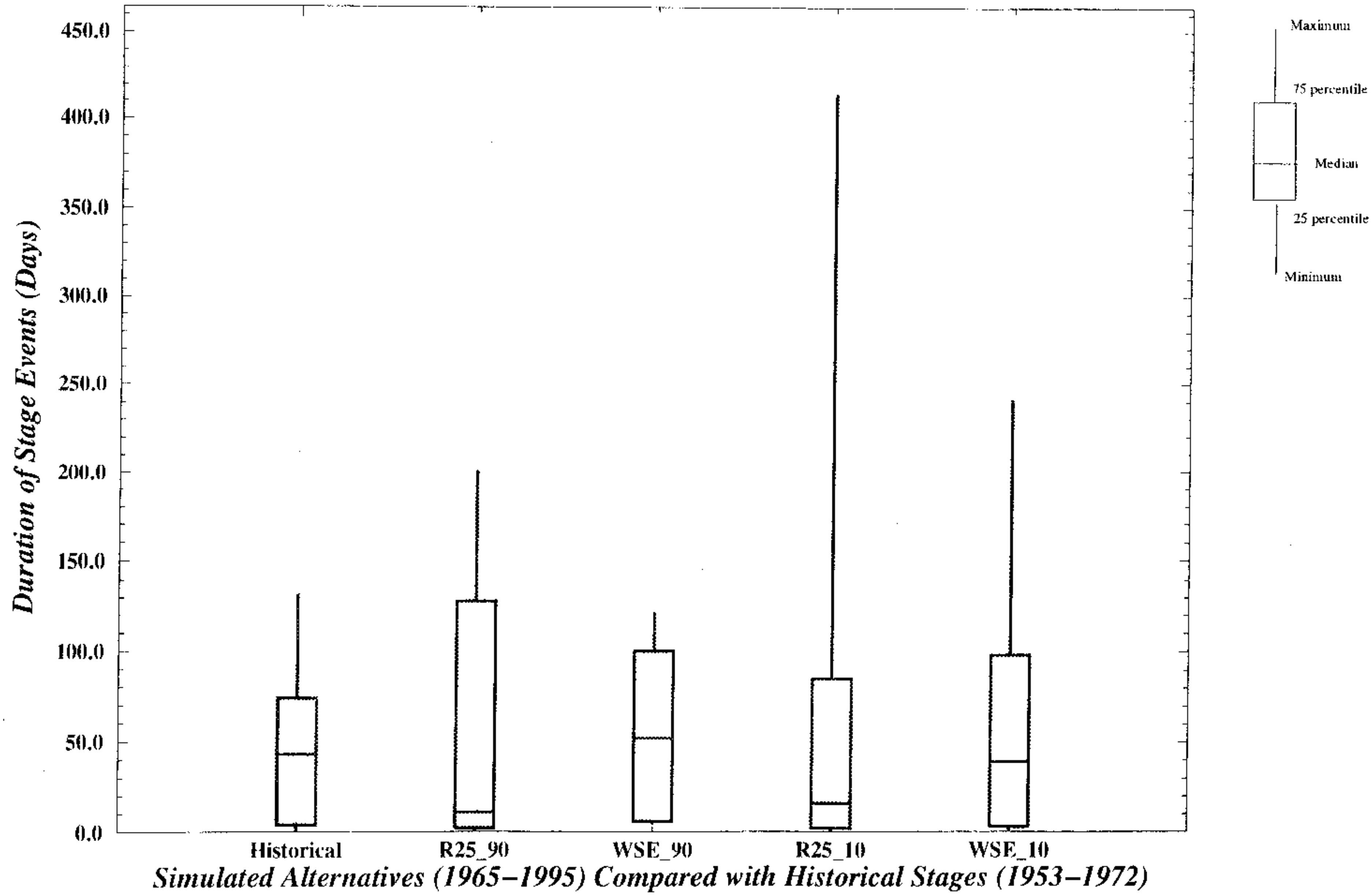
Similarity in Duration of Stage Events > 15 feet



Run date: 04/24/98 15:29:08
For Planning Purposes Only
SFWMM V3.2

Lake Okeechobee Littoral Zone

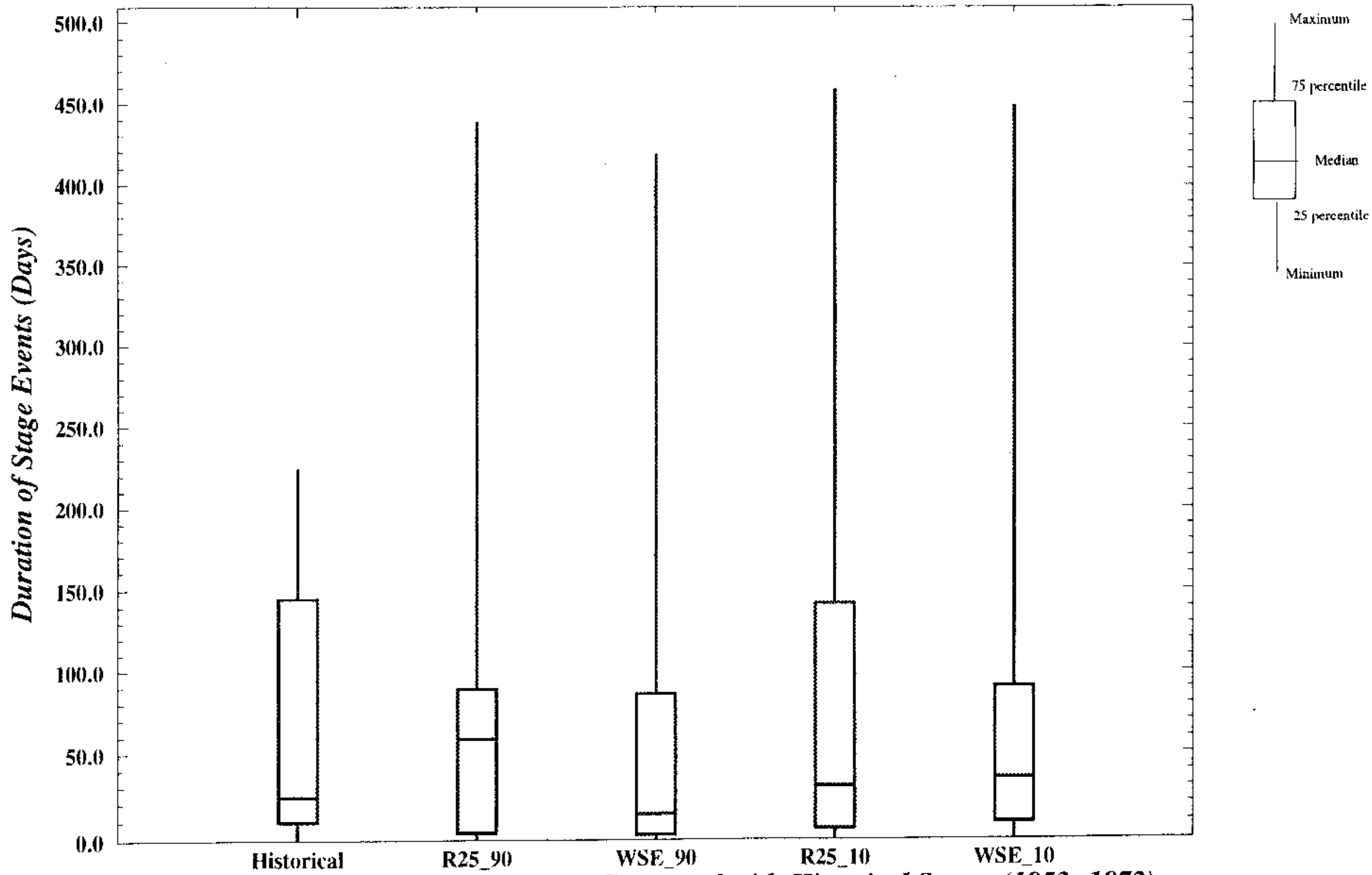
Similarity in Duration of Stage Events < 11 feet



Run date: 04/24/98 15:28:52
For Planning Purposes Only

Lake Okeechobee Littoral Zone

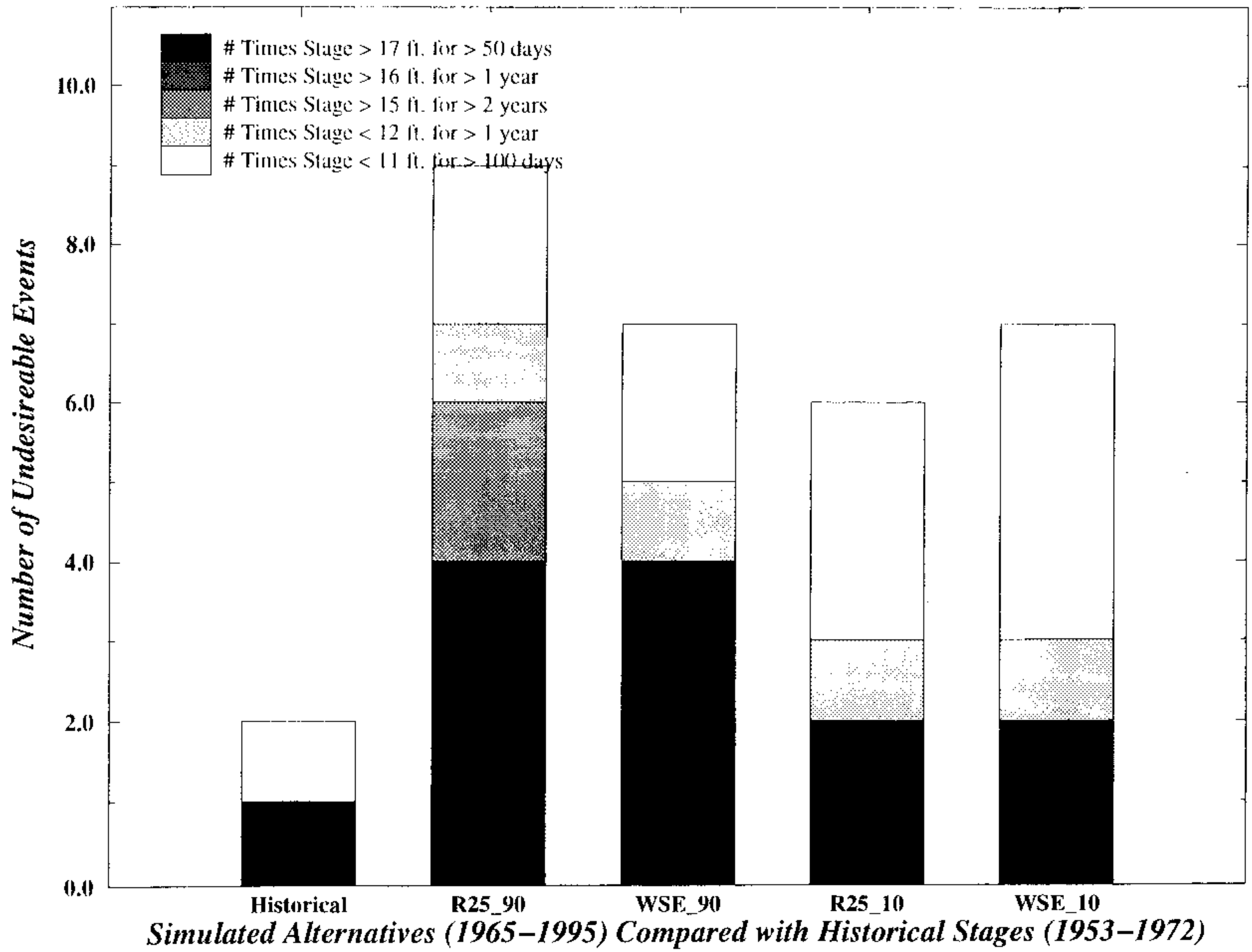
Similarity in Duration of Stage Events < 12 feet



Simulated Alternatives (1965–1995) Compared with Historical Stages (1953–1972)

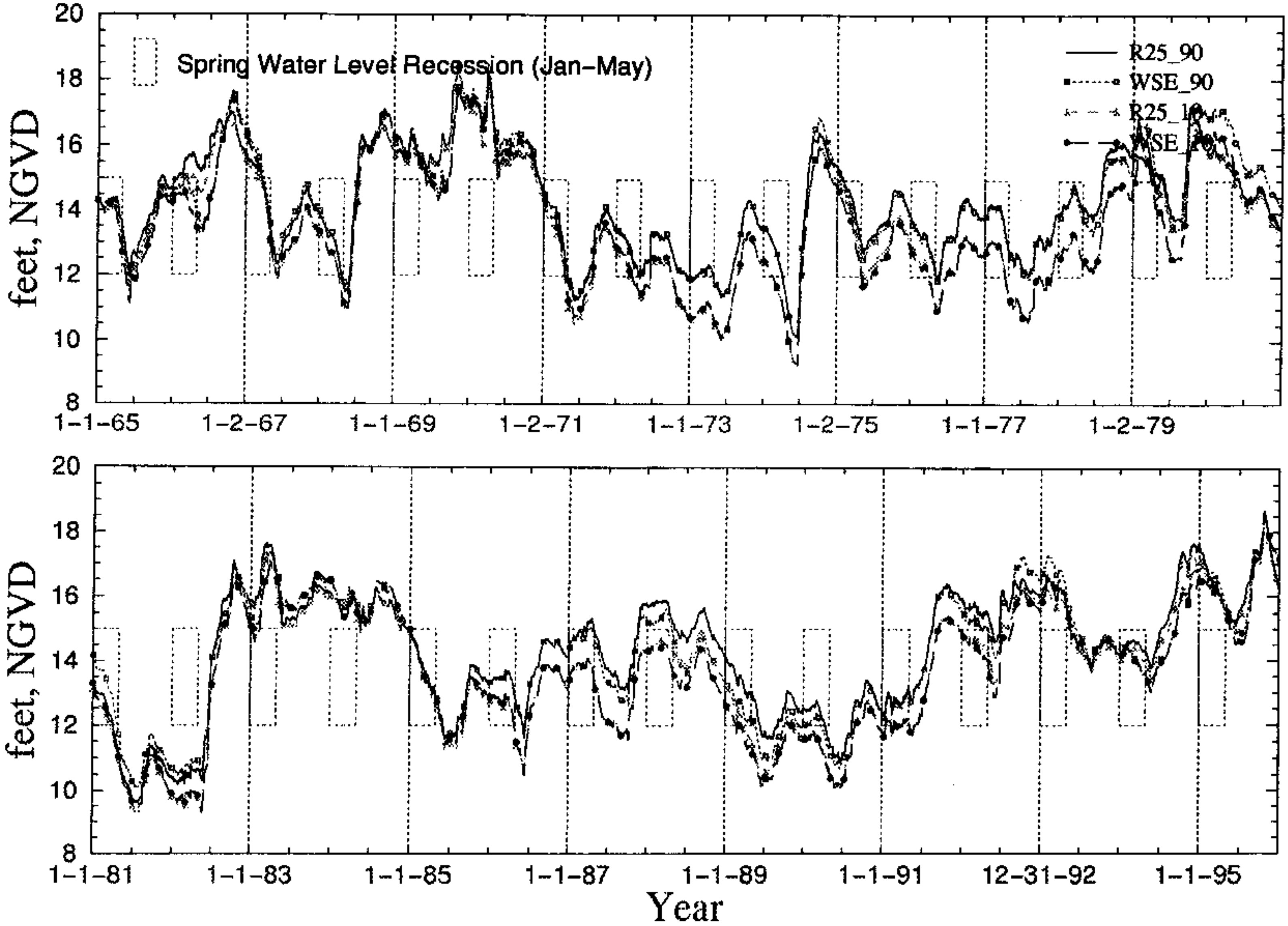
Run date: 04/24/98 15:29:00
For Planning Purposes Only
SFWMM V3.2

Number of Undesireable Lake Okeechobee Stage Events



Run date: 04/24/98 15:28:28
For Planning Purposes Only

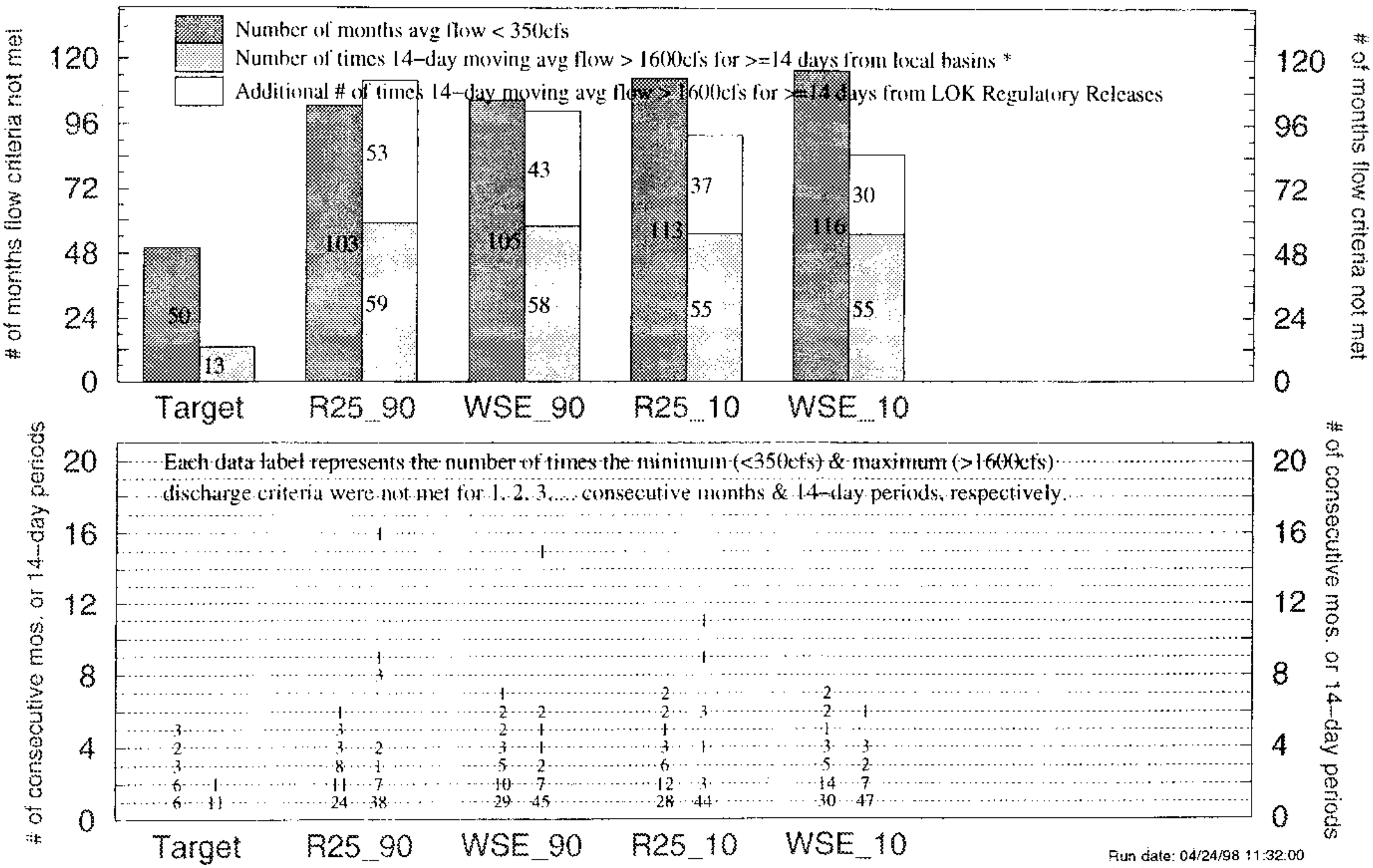
Daily Stage Hydrographs for Lake Okeechobee
Spring Water Level Recession Windows



Run date: 04/24/98 12:16:27
For Planning Purposes Only
SFWMM V3.2

Performance Measures for the
Caloosahatchee and St. Lucie Estuaries

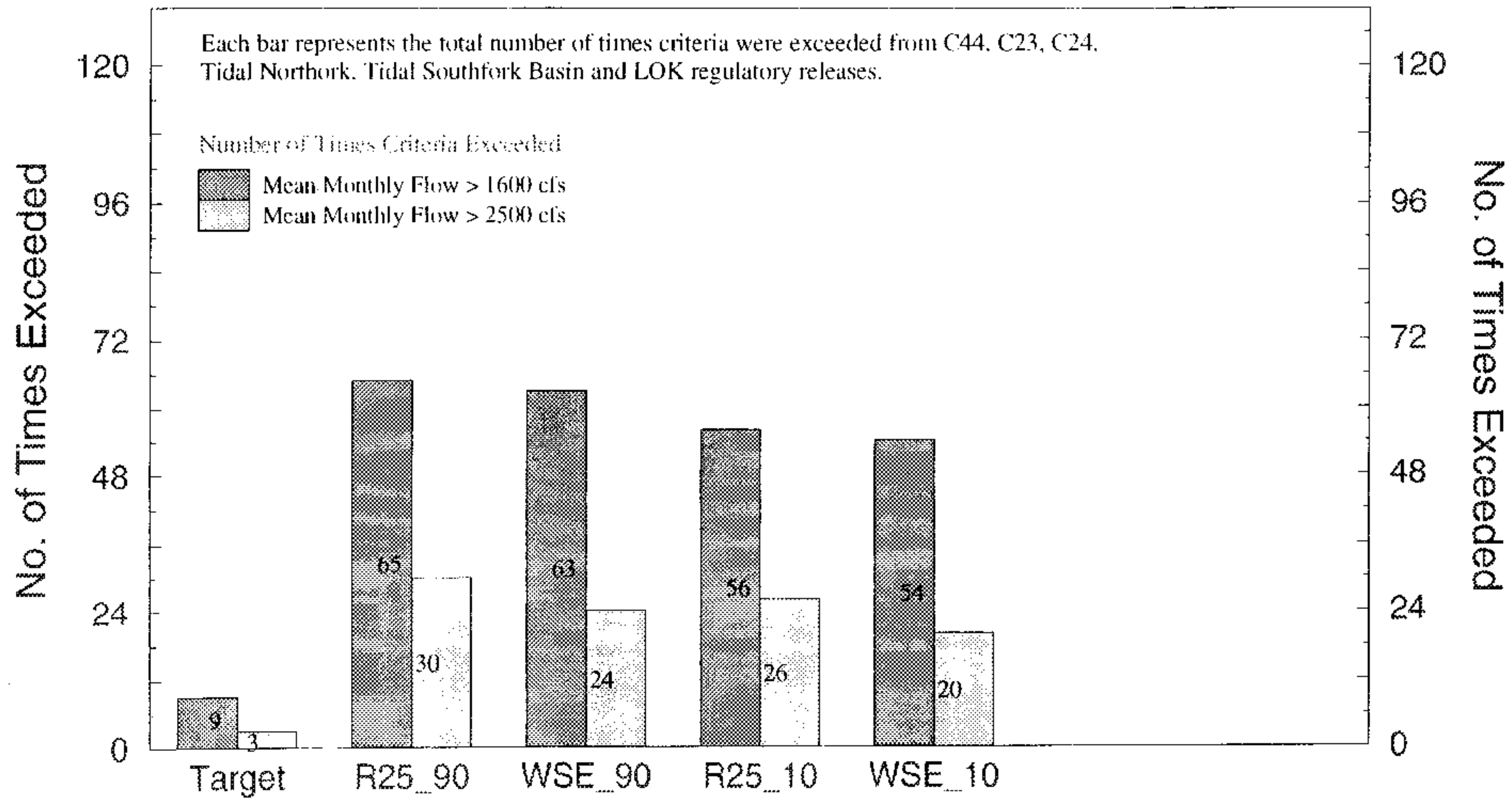
Number of times Salinity Envelope Criteria were NOT met for the St. Lucie Estuary



Note: local basins include the C-44, C-23, C-24, North Fork, and South Fork Basins

Run date: 04/24/98 11:32:00
For Planning Purposes Only
SFWMM V3.2

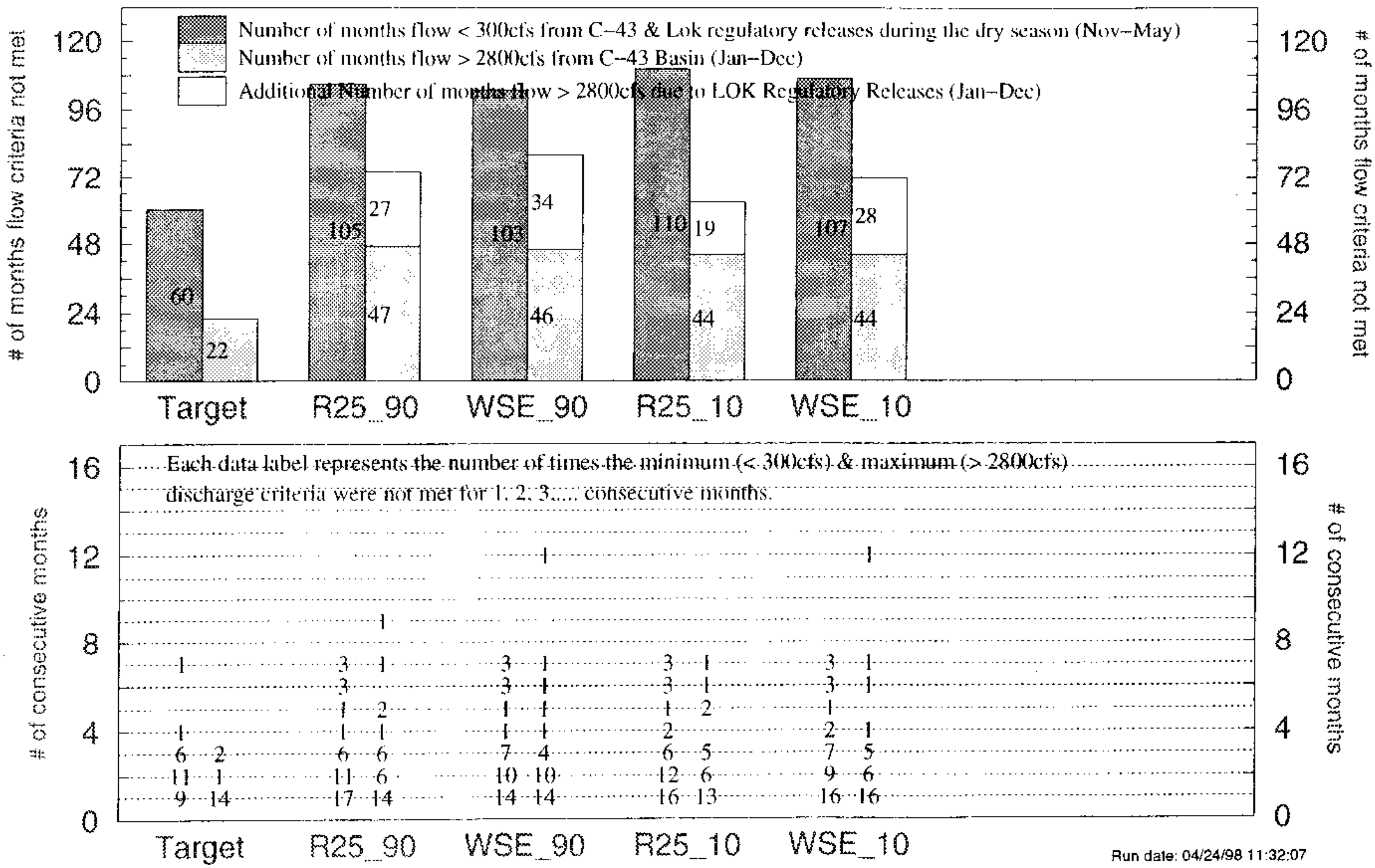
Number of Times High Discharge Criteria (mean monthly flows > 1600 & 2500 cfs) were exceeded for the St. Lucie Estuary



Note: A favorable maximum monthly flow was developed for the estuary (1600 cfs) that will theoretically provide suitable salinity conditions which promote the development of important benthic communities (eg. oysters & shoalgrass). Mean monthly flows above 2500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota.

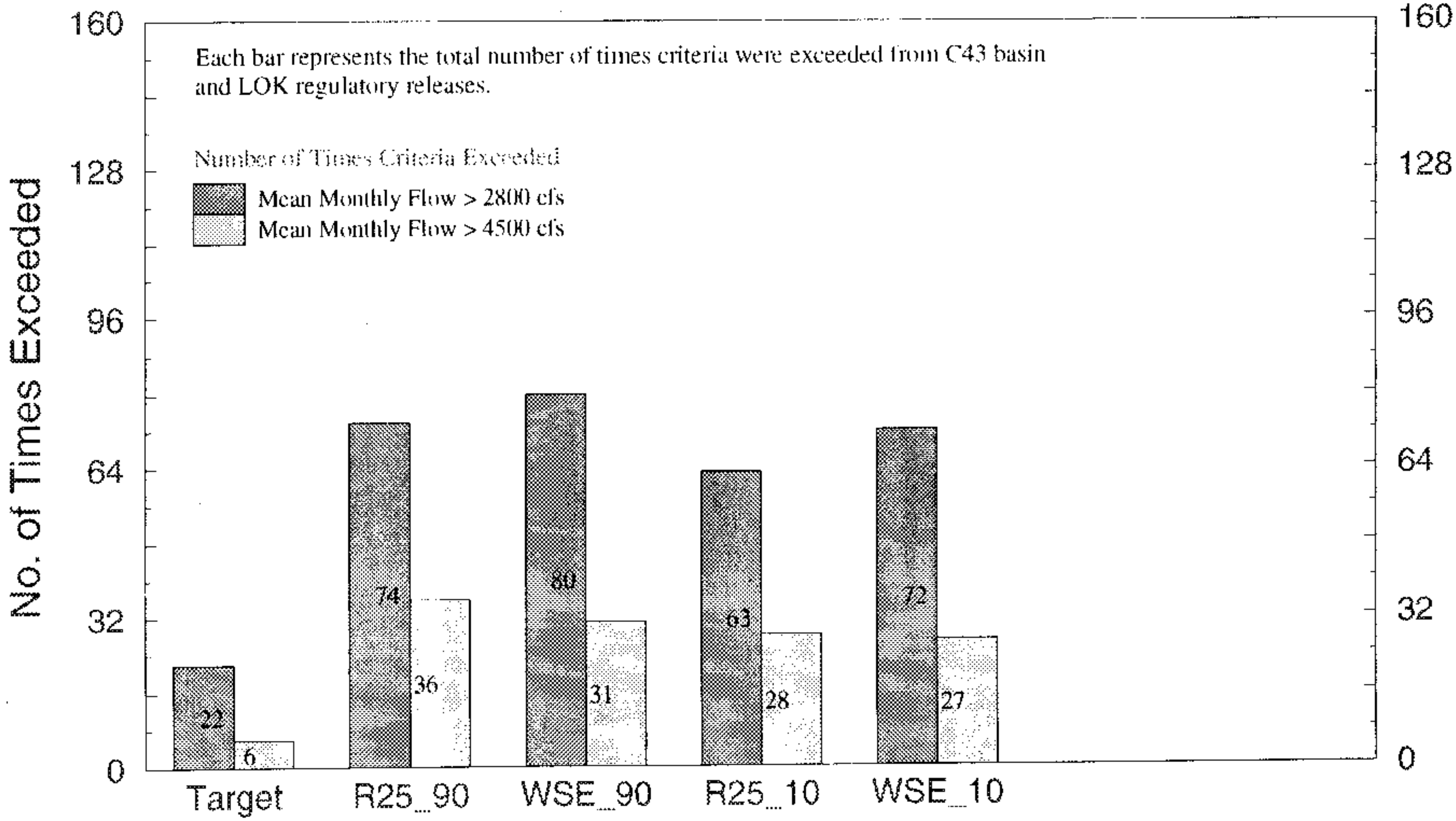
Run date: 04/24/98 11:32:05
For Planning Purposes Only

Number of times Salinity Envelope Criteria were NOT met for the Caloosahatchee Estuary (mean monthly flows 1965 – 1995)



Run date: 04/24/98 11:32:07
For Planning Purposes Only
SFWMM V3.2

Number of Times High Discharge Criteria (mean monthly flows > 2800 & 4500 cfs) were exceeded for the Caloosahatchee Estuary

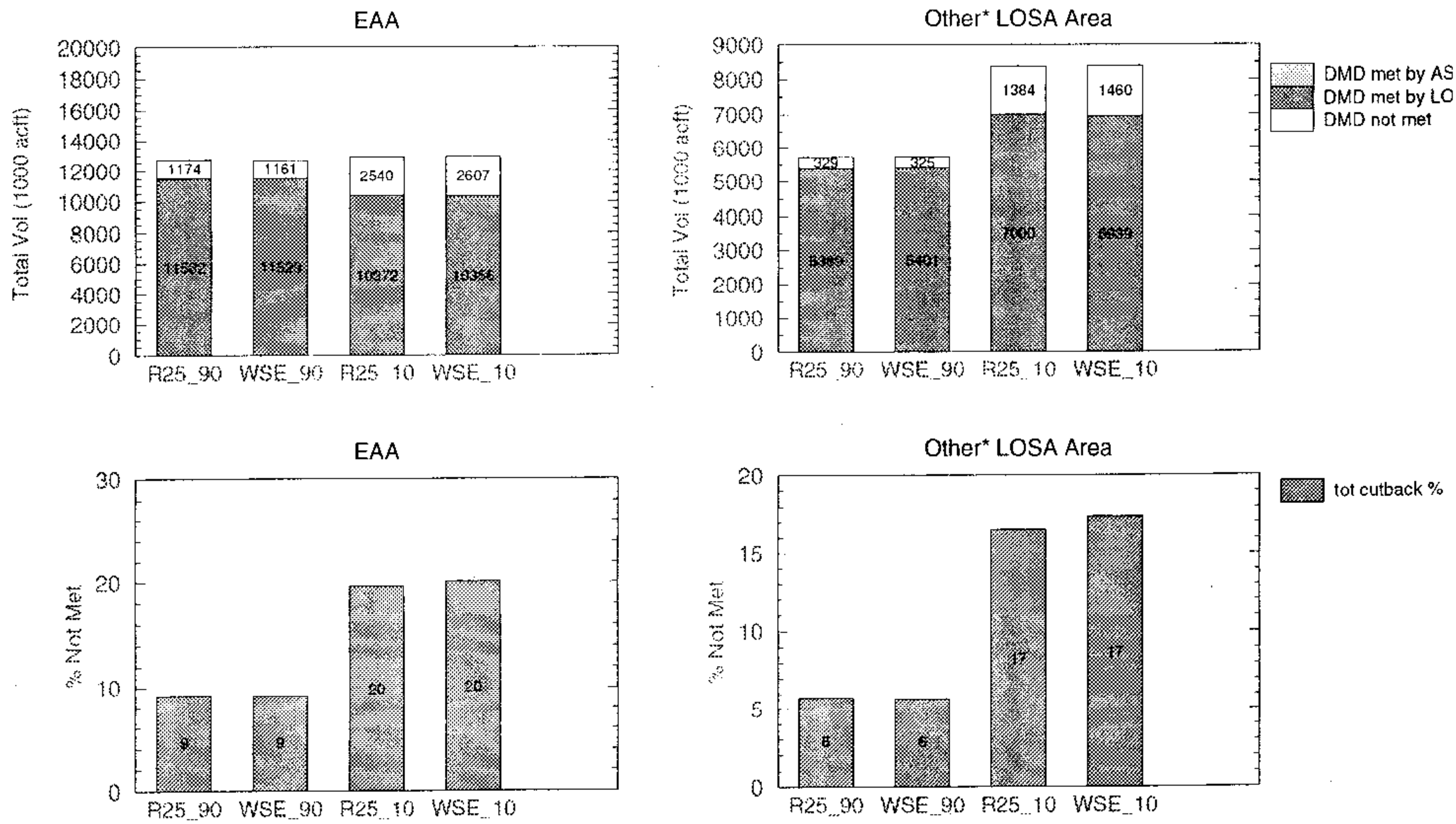


Run date: 04/24/98 11:32:13
For Planning Purposes Only

Performance Measures for the
Lake Okeechobee Service Area

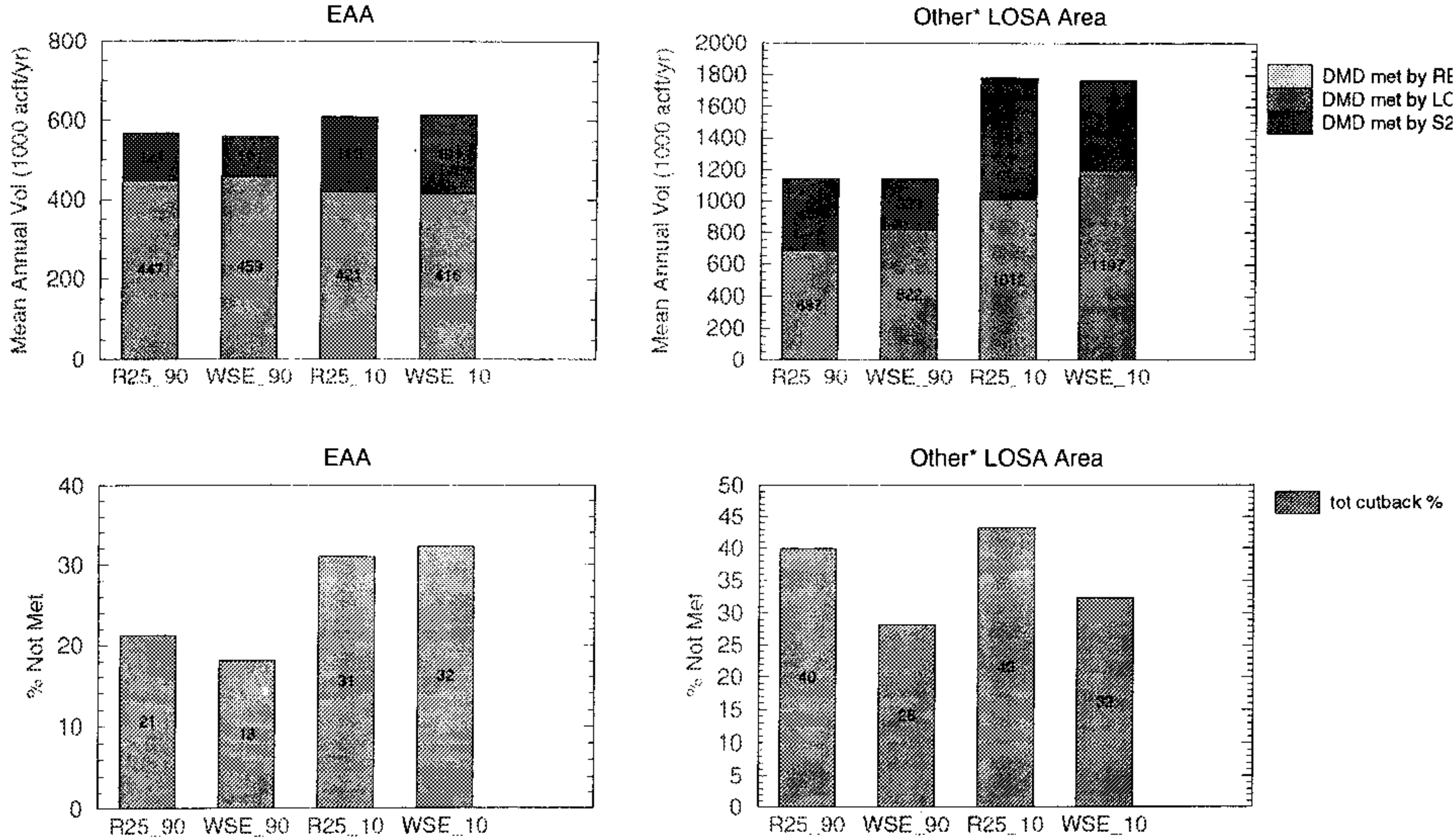
Total EAA/LOSA Irrigation Demands and Demands Not Met

for the 1965 – 1995 Simulation Period



*Other Lake Service SubAreas (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

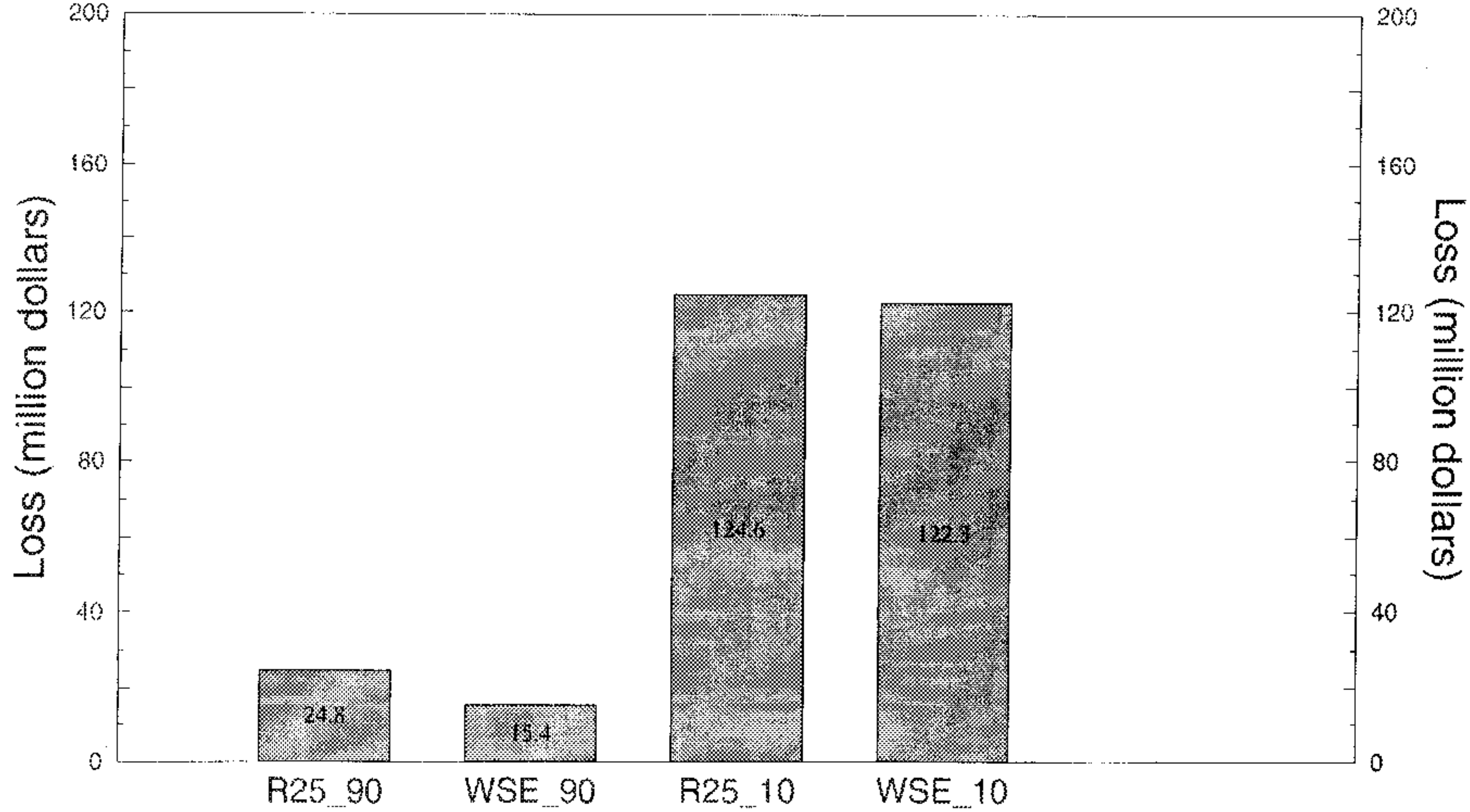
Mean Annual EAA/LOSA Supplemental Irrigation:
Demands and Demands Not Met for the Drought Years:
1971, 1975, 1981, 1985, 1989 within the 1965 – 1995 Simulation Period



*Other Lake Service SubAreas (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

Run date: 04/29/98 10:37:29
For Planning Purposes Only

EAA IRRIGATED AREA ECONOMIC LOSSES
Total Losses Due to ET Reduction for 31 yr. simulation

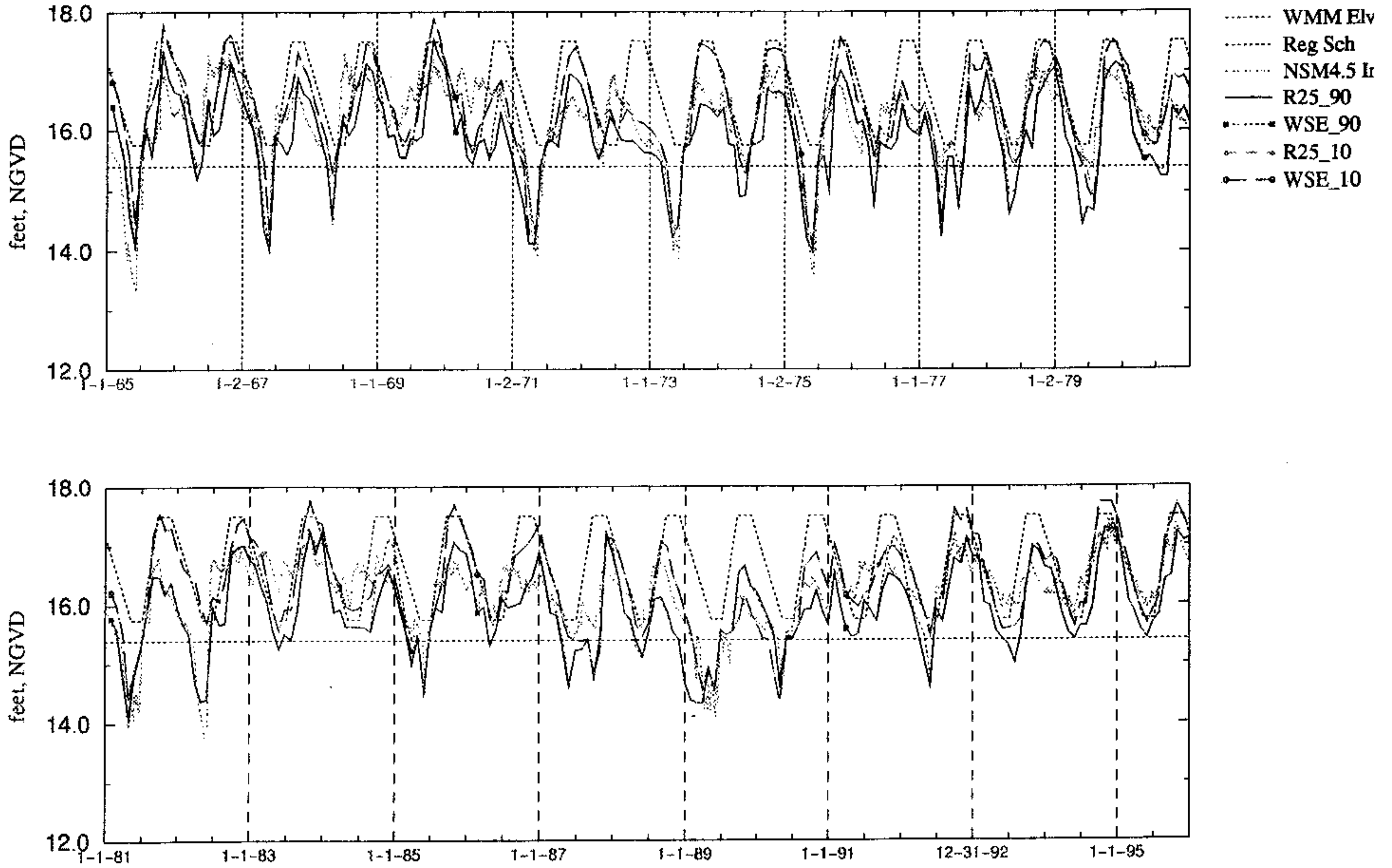


Note: Losses are based on Yield Reductions for Sugarcane in the EAA.
Sugarcane acreage(acres): 529,920(1990) 491,520(2010)

Run date: 04/24/98 10:55:15
For Planning Purposes Only
SFWMM V3.2

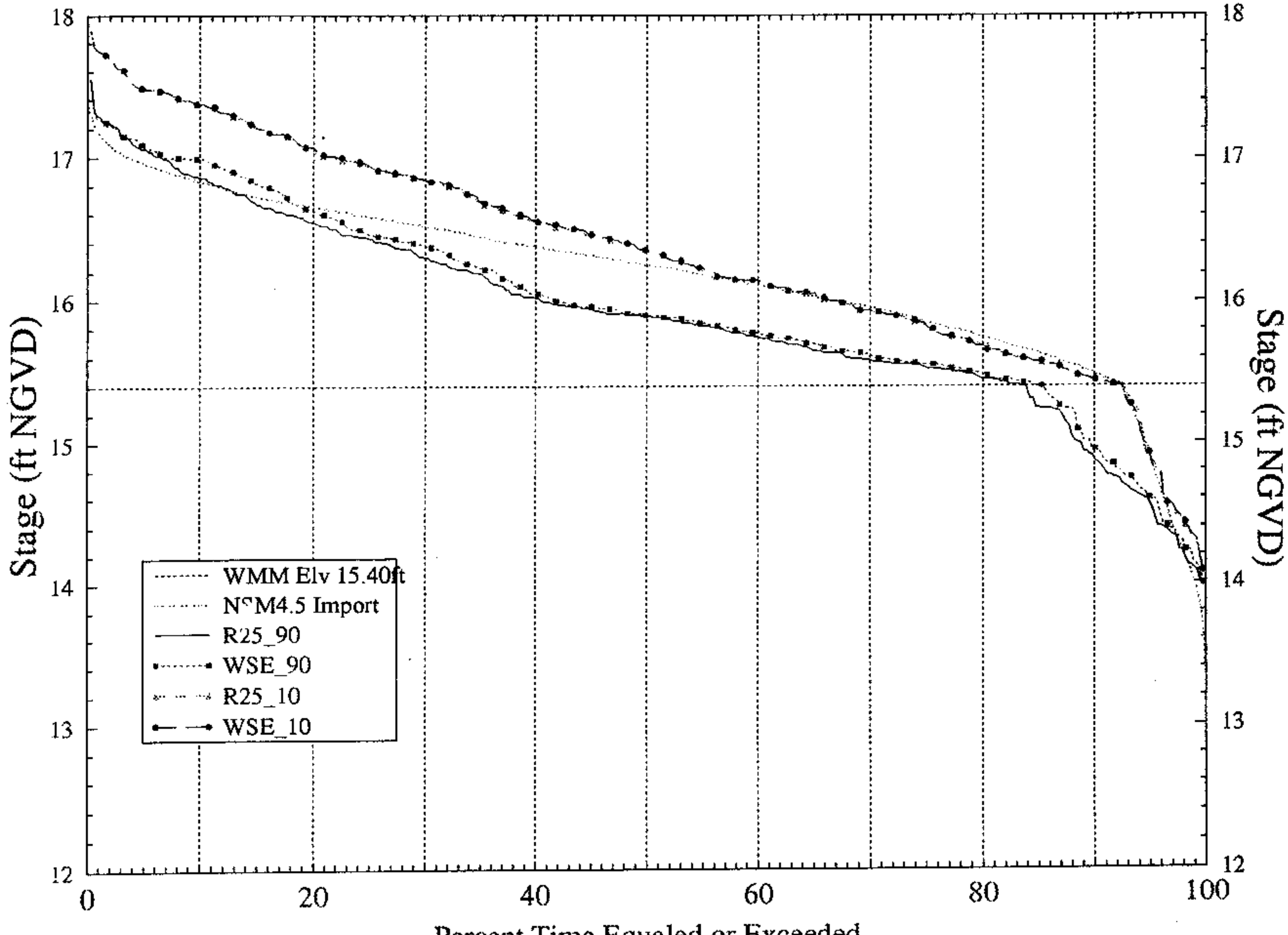
Performance Measures for the
Everglades WCAs

Import Stage Hydrograph for WCA-1
Gage 1-7 Cell R48 C31



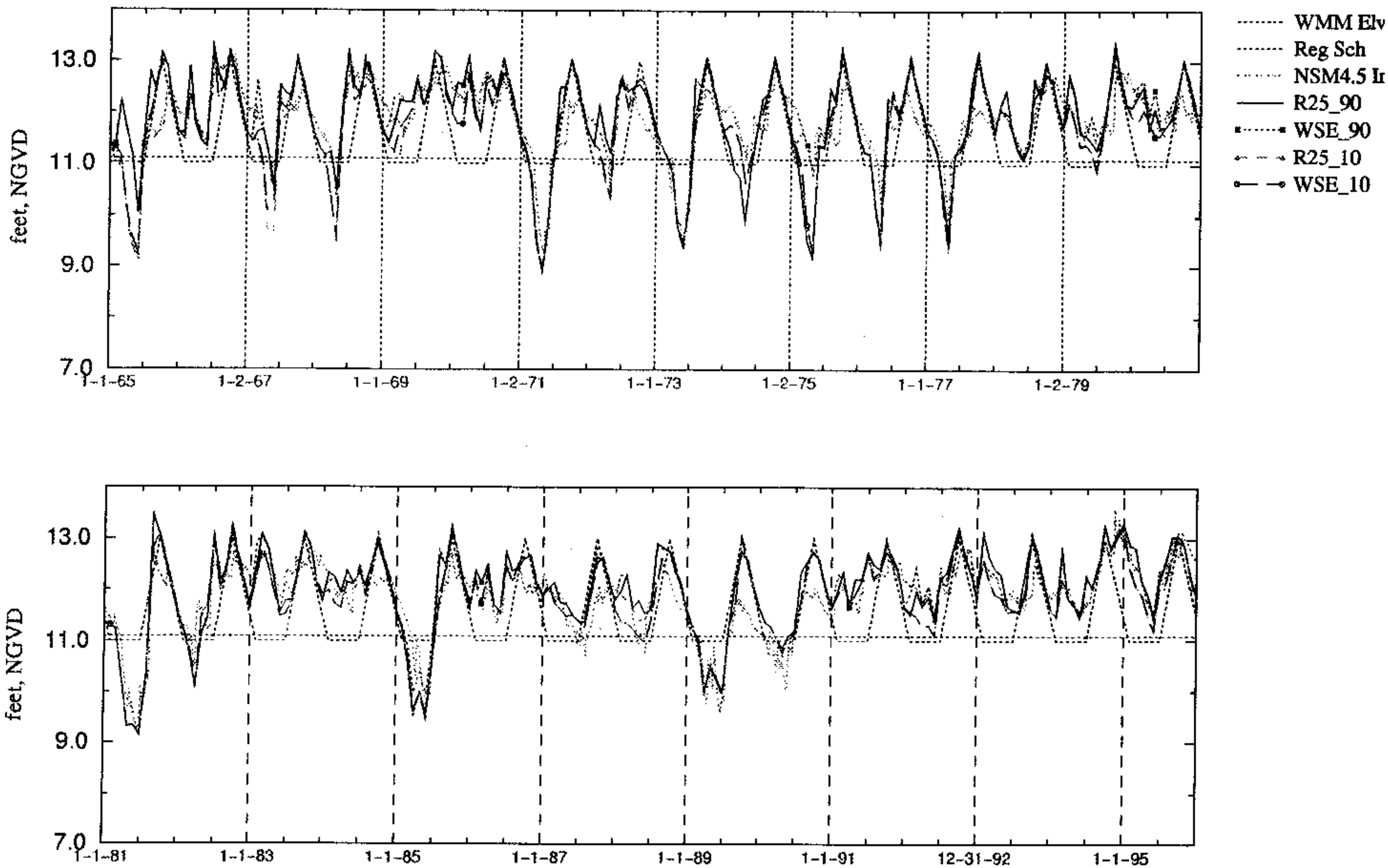
Run date: 04/24/98 11:03:45
For Planning Purposes Only
SFWMM V3.2

Import Stg Duration Curves for WCA−1
Gage 1−7 Cell R48 C31



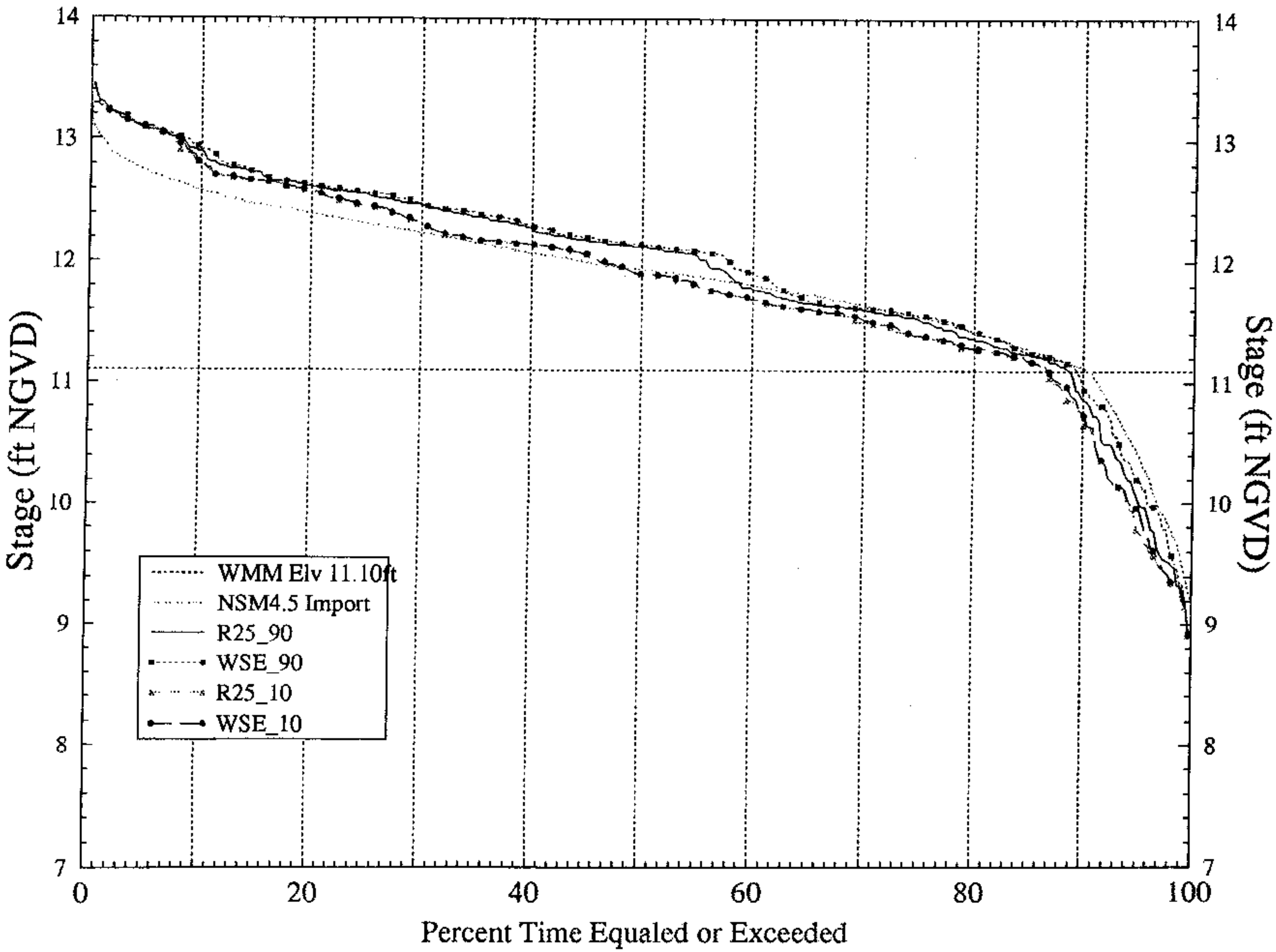
Run date: 04/24/98 11:03:50
For Planning Purposes Only

Import Stage Hydrograph for WCA-2A
Gage 2-17 Cell R40 C29



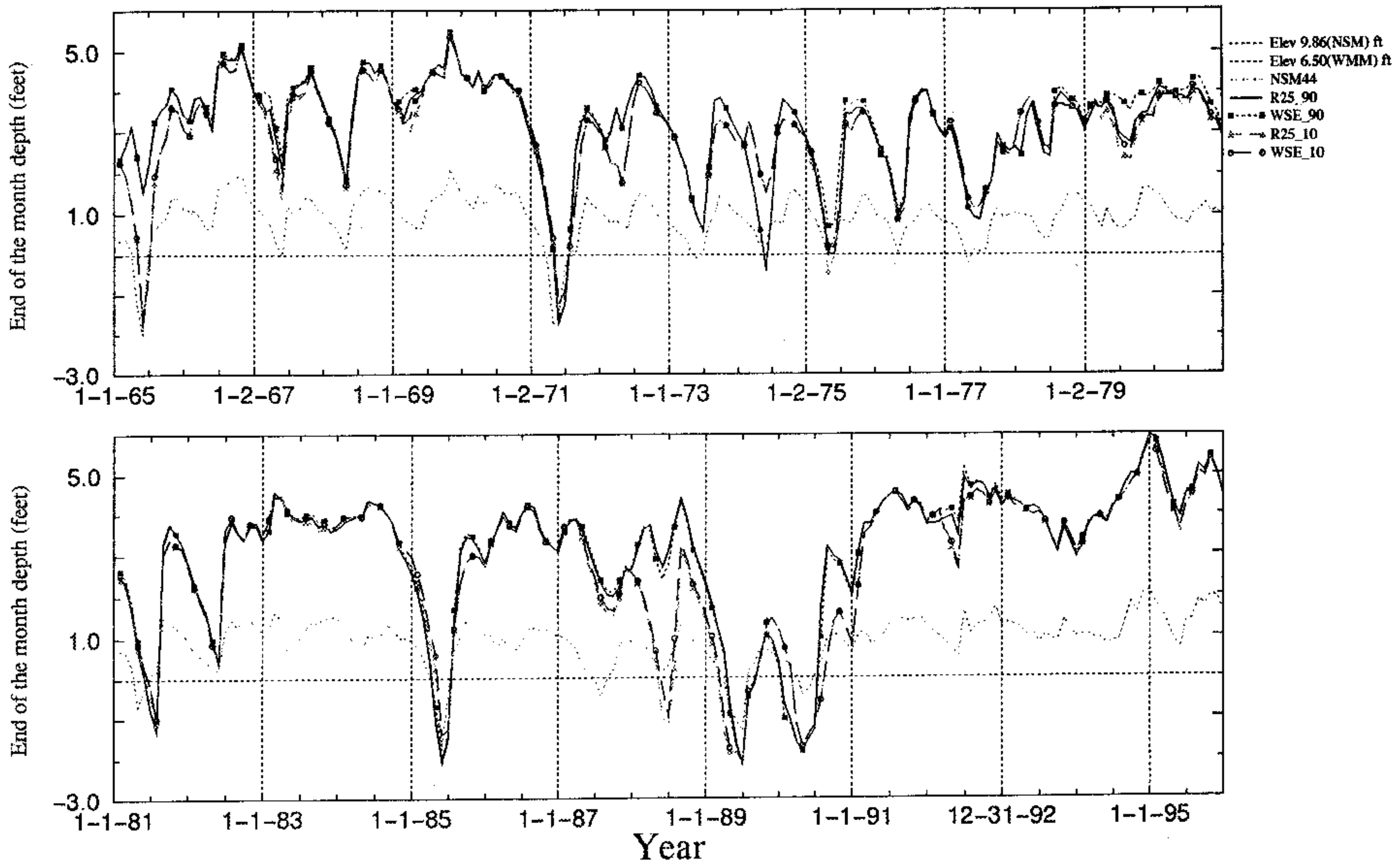
Run date: 04/24/98 11:03:37
For Planning Purposes Only
SFWMM V3.2

Import Stg Duration Curves for WCA–2A
Gage 2–17 Cell R40 C29



Run date: 04/24/98 11:03:41
For Planning Purposes Only

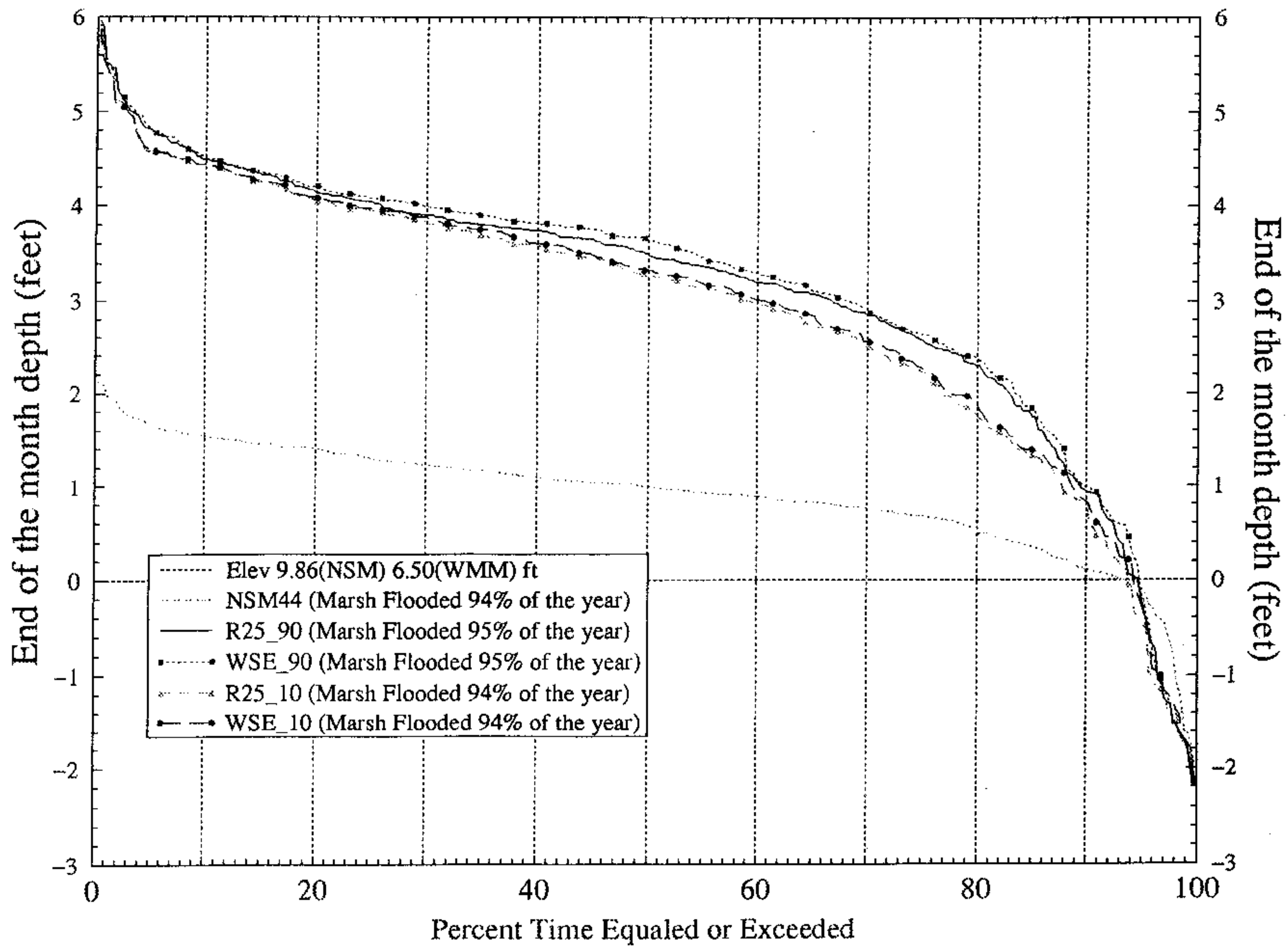
Normalized Stage Hydrograph at Cell (R35 C30)
South End of WCA-2B (Gage 2B-21)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 04/28/98 09:41:30
For Planning Purposes Only
SFWMM V3.2

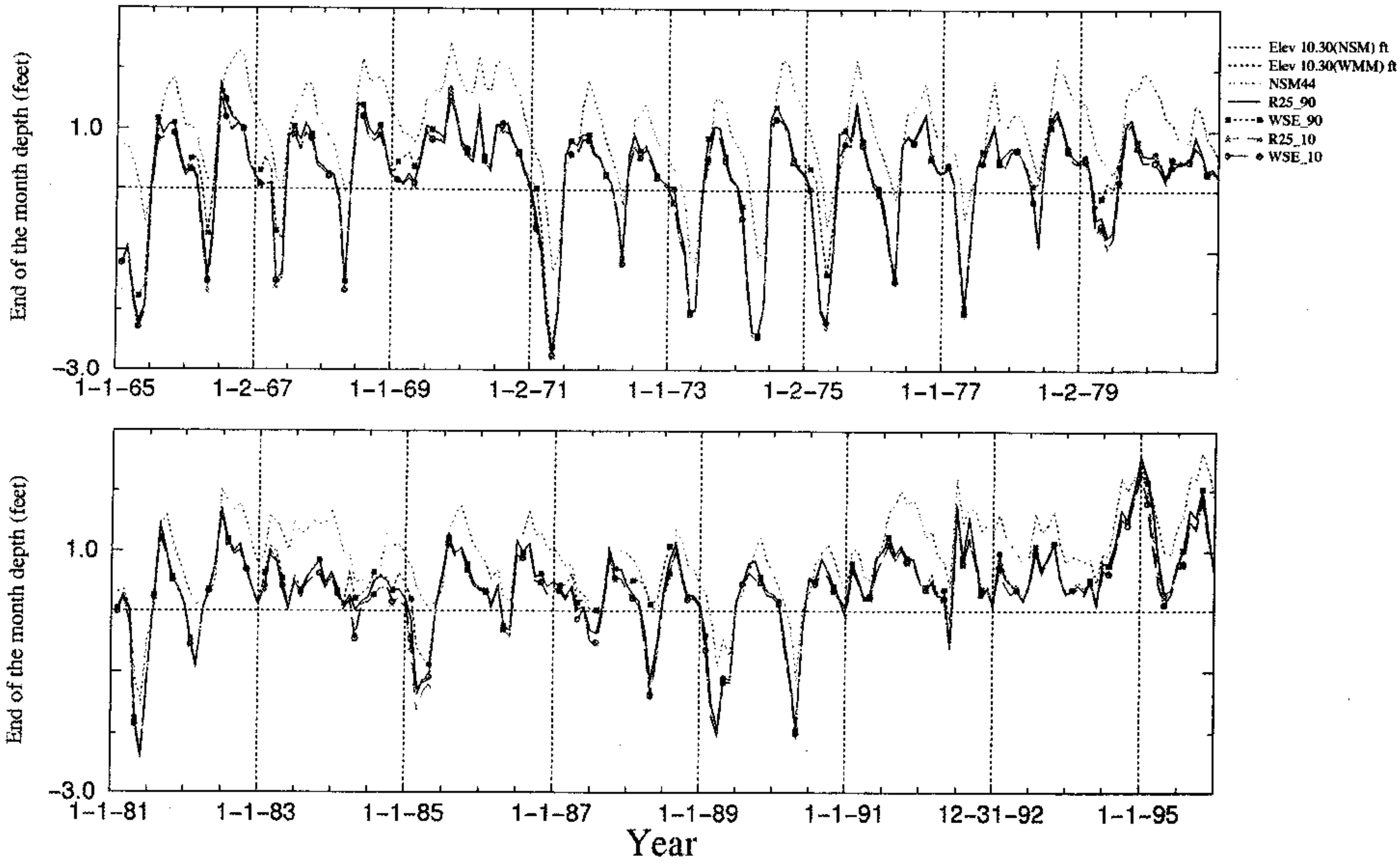
Normalized Stage Duration Curves at Cell (R35 C30)
South End of WCA-2B (Gage 2B-21)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

Run date: 04/28/98 09:41:24
For Planning Purposes Only

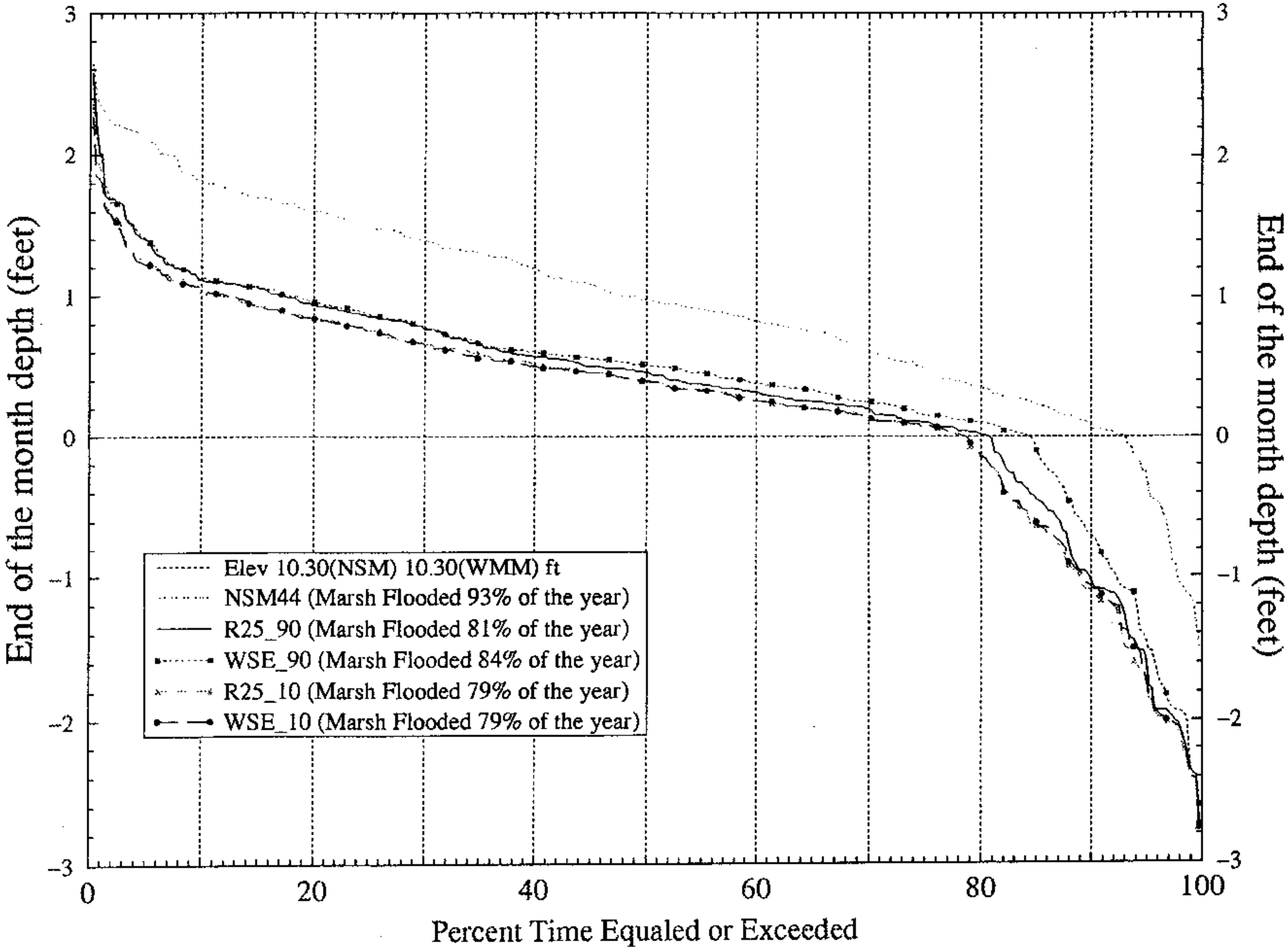
Normalized Stage Hydrograph at Cell (R36 C18)
North End of WCA−3A (Gage 3A−2)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 04/28/98 09:49:46
For Planning Purposes Only
SFWMM V3.2

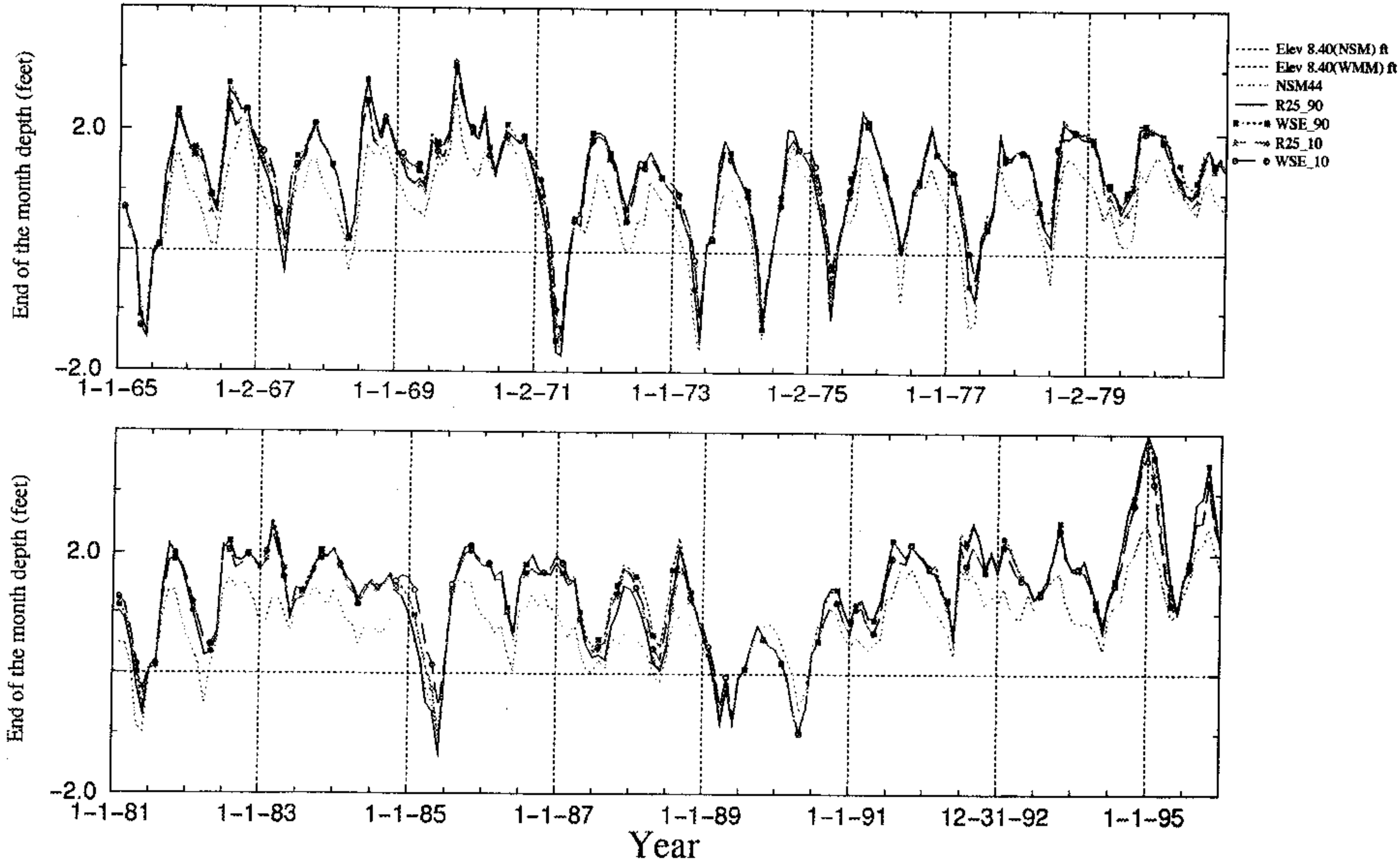
Normalized Stage Duration Curves at Cell (R36 C18)
North End of WCA-3A (Gage 3A-2)



Run date: 04/28/98 09:49:39
For Planning Purposes Only
SFWMM V3.2

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

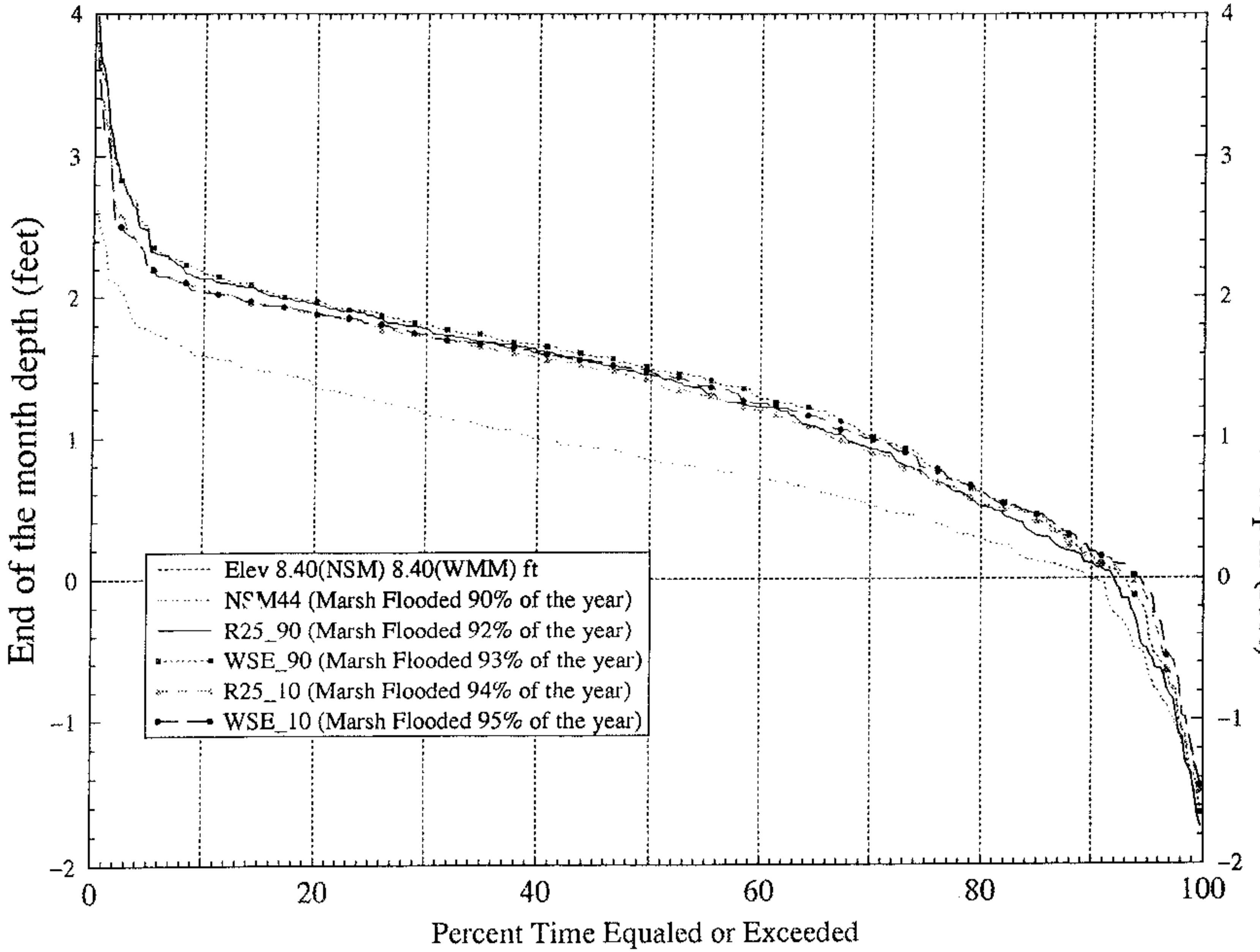
Normalized Stage Hydrograph at Cell (R29 C21)
Central Portion of WCA-3A(Gage 3A-4)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 04/28/98 09:50:08
For Planning Purposes Only
SFWMM V3.2

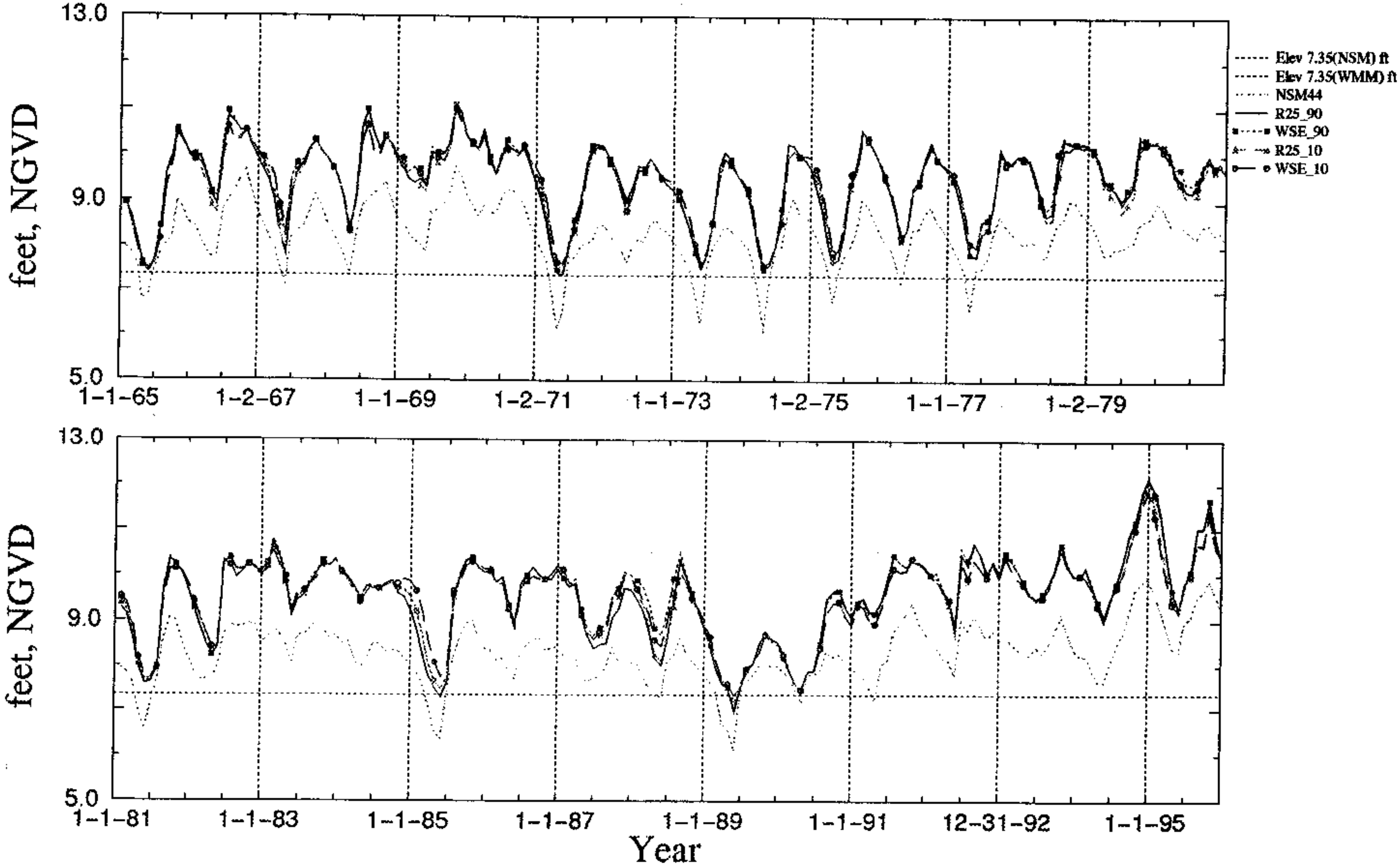
Normalized Stage Duration Curves at Cell (R29 C21)
Central Portion of WCA–3A(Gage 3A–4)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

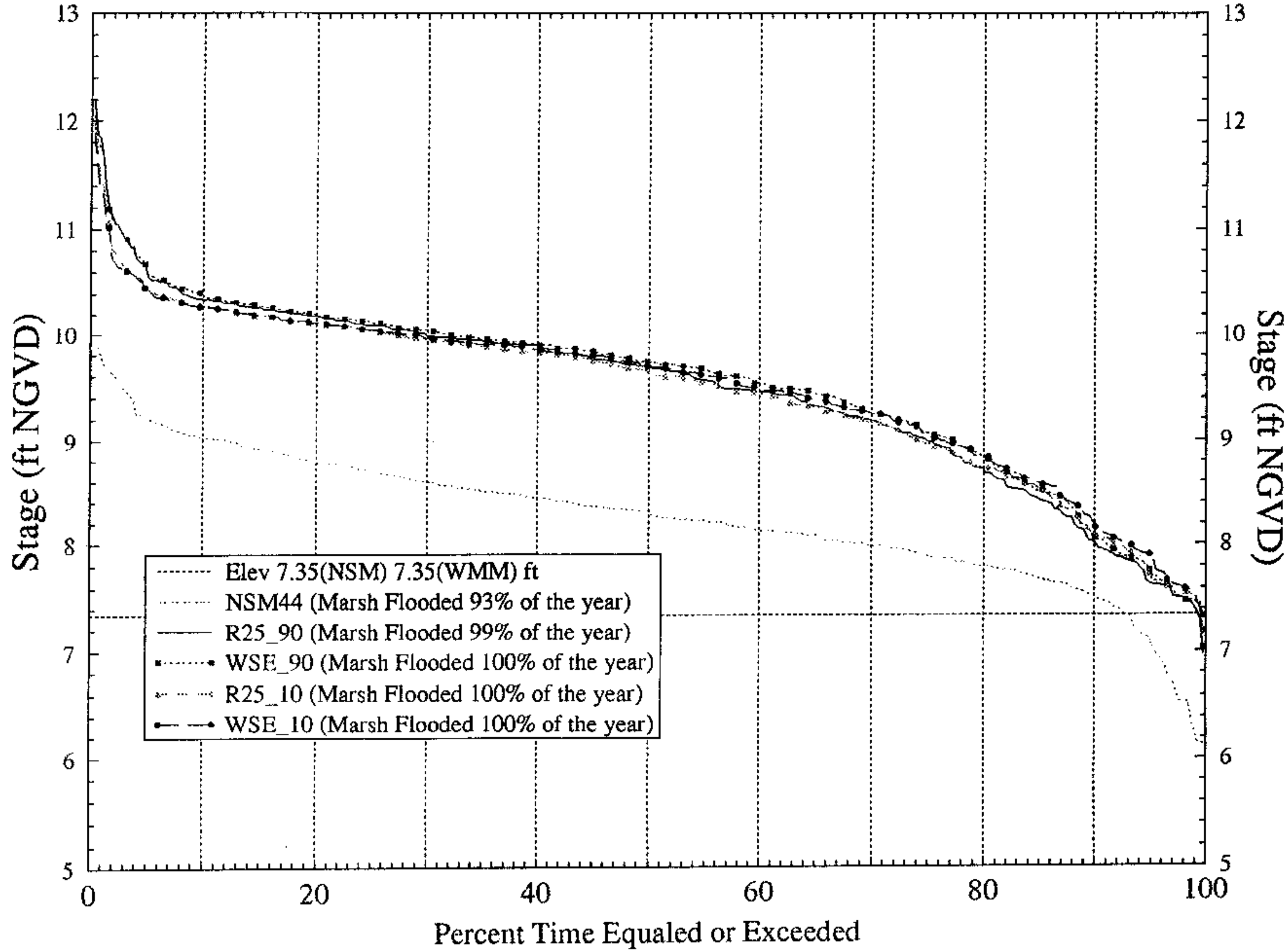
Run date: 04/28/98 09:50:01
For Planning Purposes Only

Stage Hydrograph for South End of WCA-3A
(Gage 3A-28, Cell R24 C19)



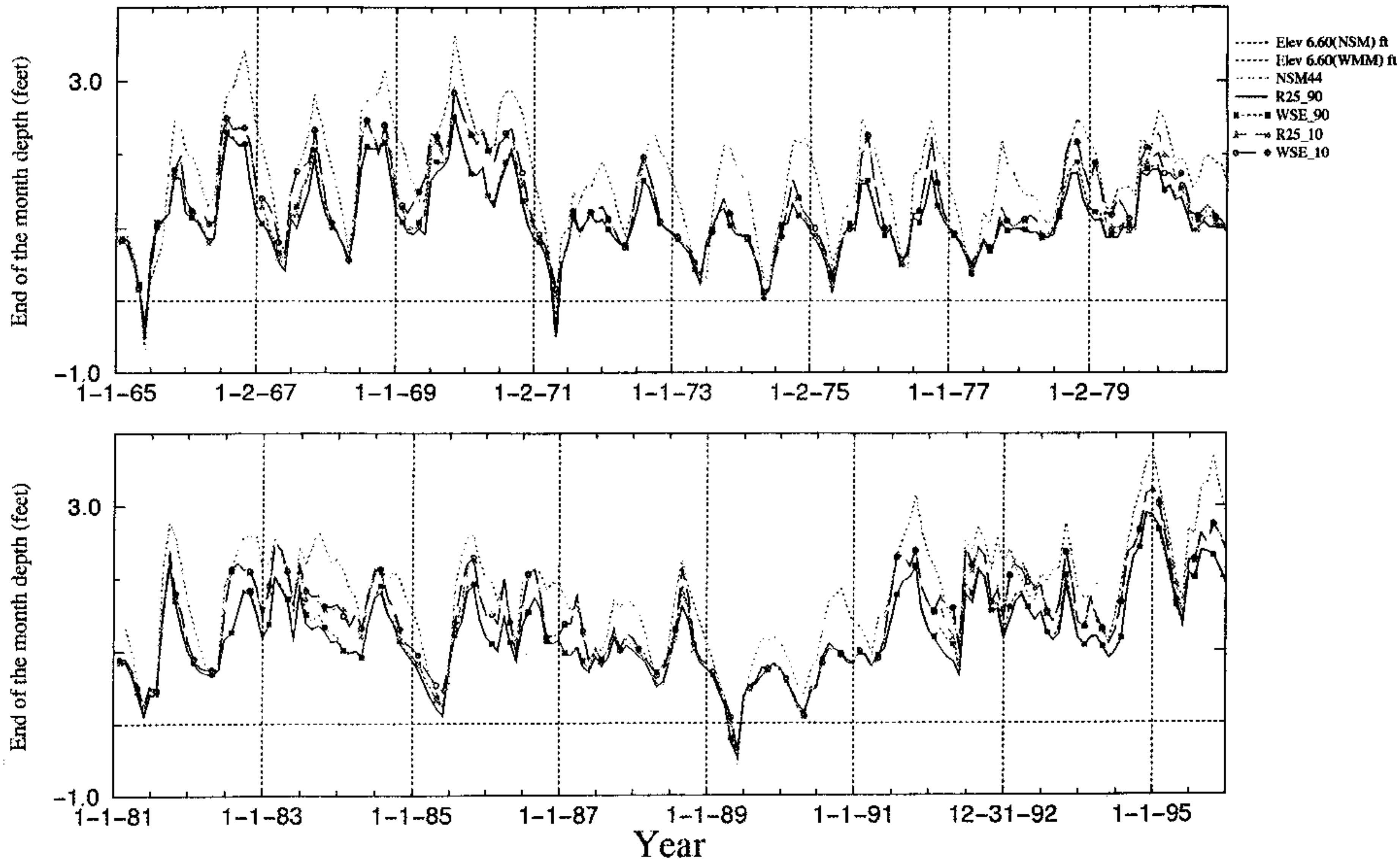
Run date: 04/24/98 12:16:39
For Planning Purposes Only
SFWMM V3.2

Stage Duration Curves at South End of WCA–3A
(Gage 3A–28, Cell R24 C19)



Run date: 04/24/98 12:15:57
For Planning Purposes Only

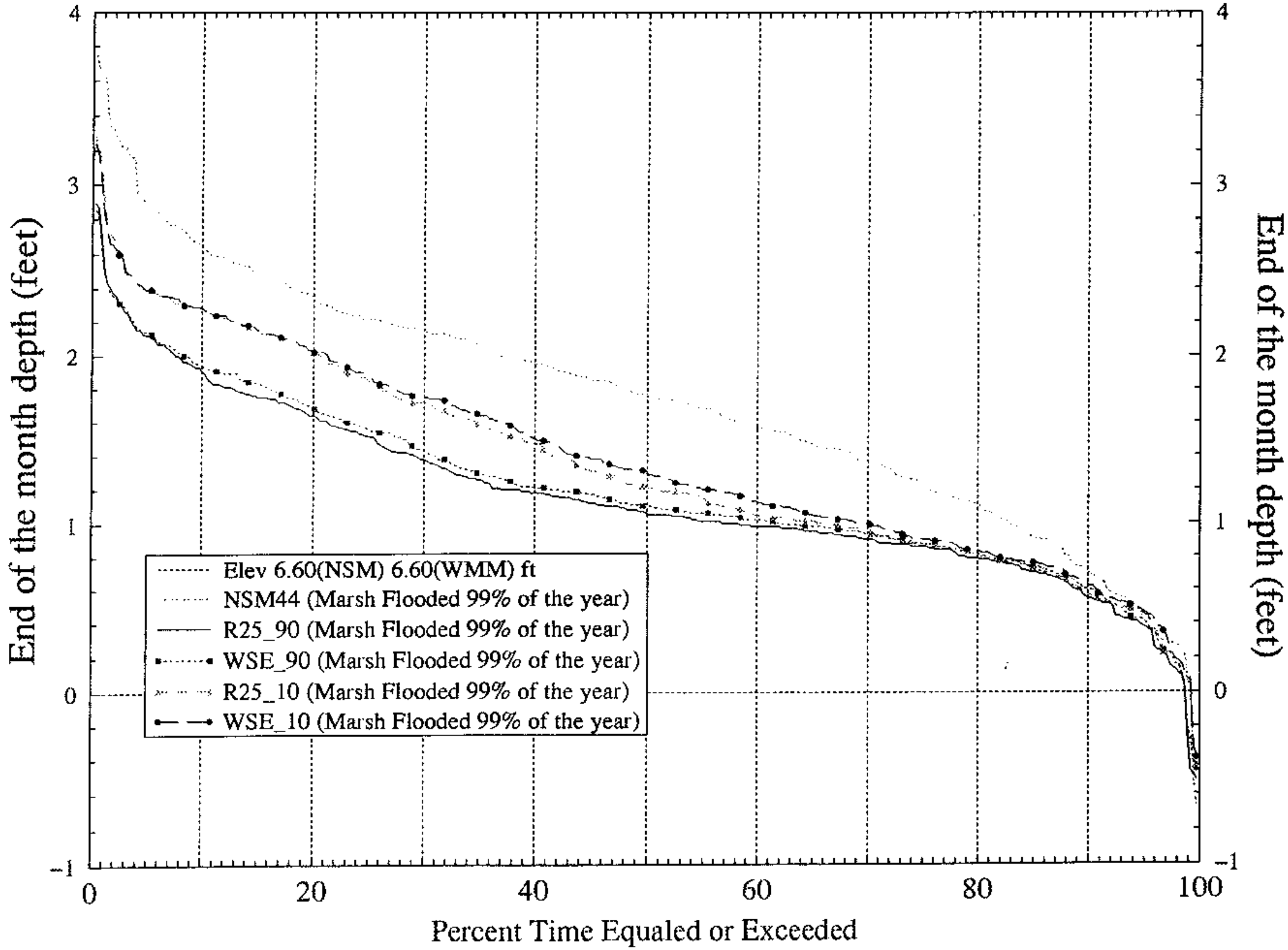
Normalized Stage Hydrograph at Cell (R26 C24) West–Central WCA–3B (Gage 3B–2)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 04/28/98 09:51:53
For Planning Purposes Only
SFWMM V3.2

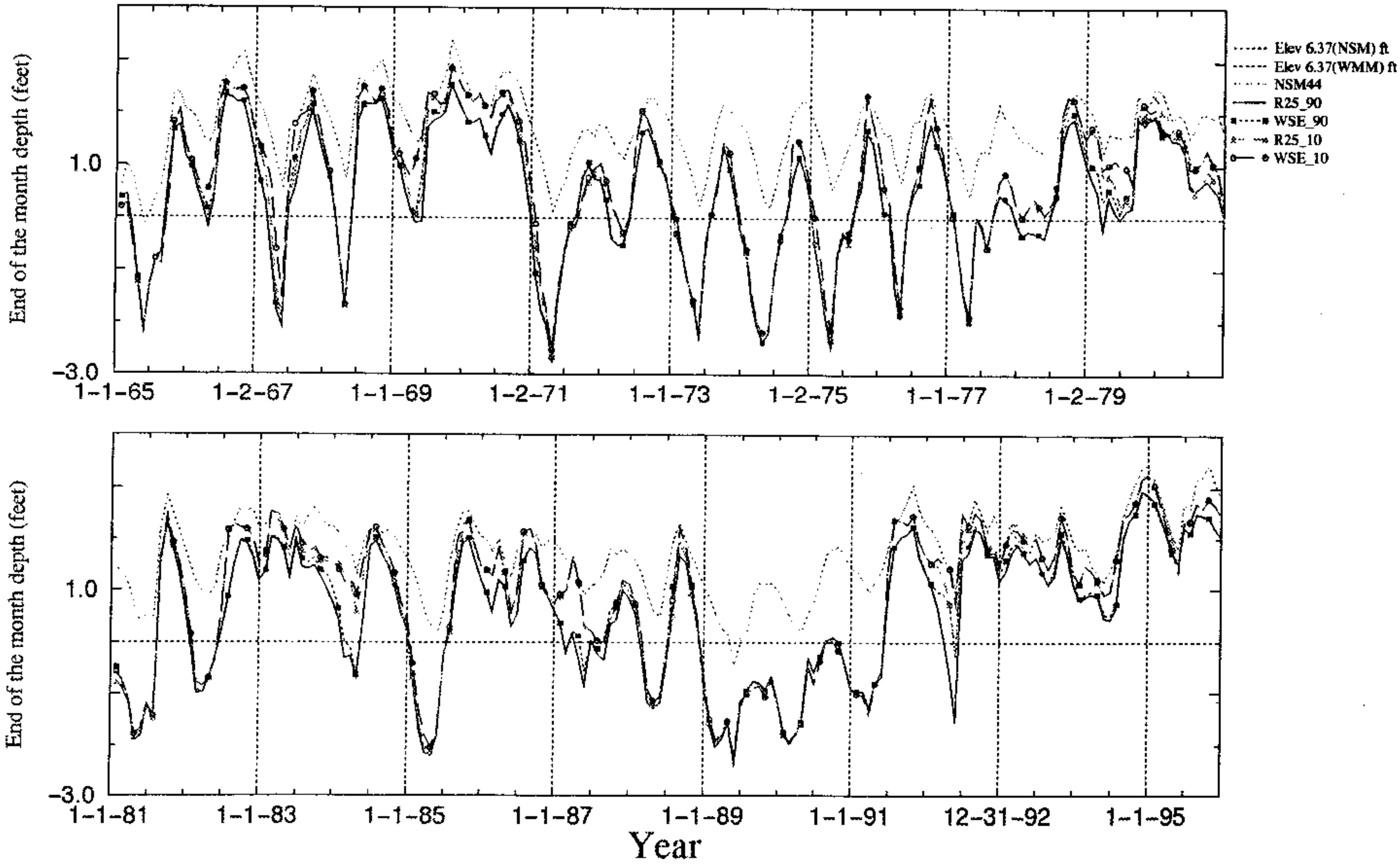
Normalized Stage Duration Curves at Cell (R26 C24)
West–Central WCA–3B (Gage 3B–2)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

Run date: 04/28/98 09:51:45
For Planning Purposes Only

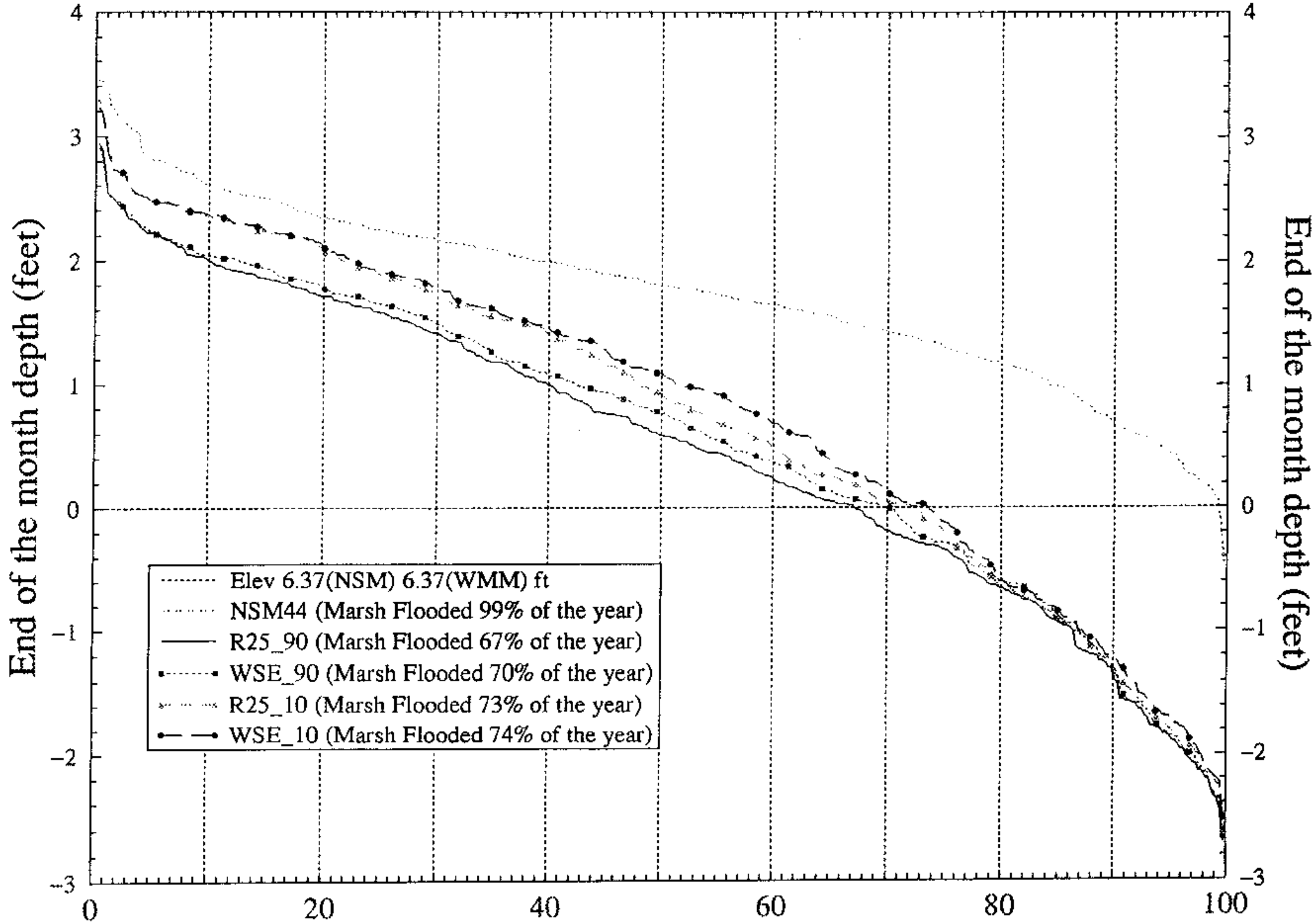
Normalized Stage Hydrograph at Cell (R23 C26)
South End of WCA-3B (Gage 3B-SE)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 04/28/98 09:50:35
For Planning Purposes Only
SFWMM V3.2

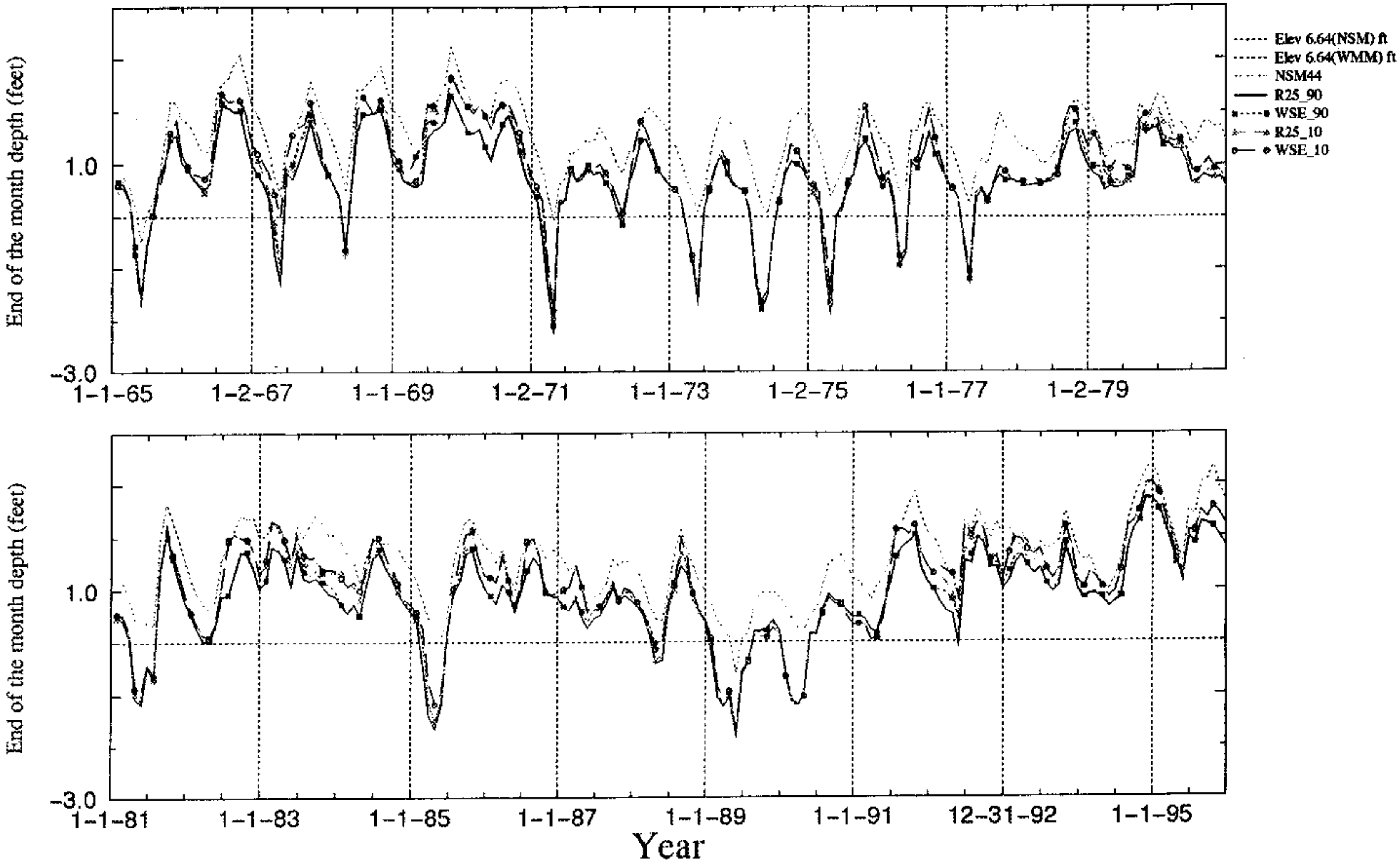
Normalized Stage Duration Curves at Cell (R23 C26)
South End of WCA–3B (Gage 3B–SE)



Run date: 04/28/98 09:50:24
For Planning Purposes Only

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

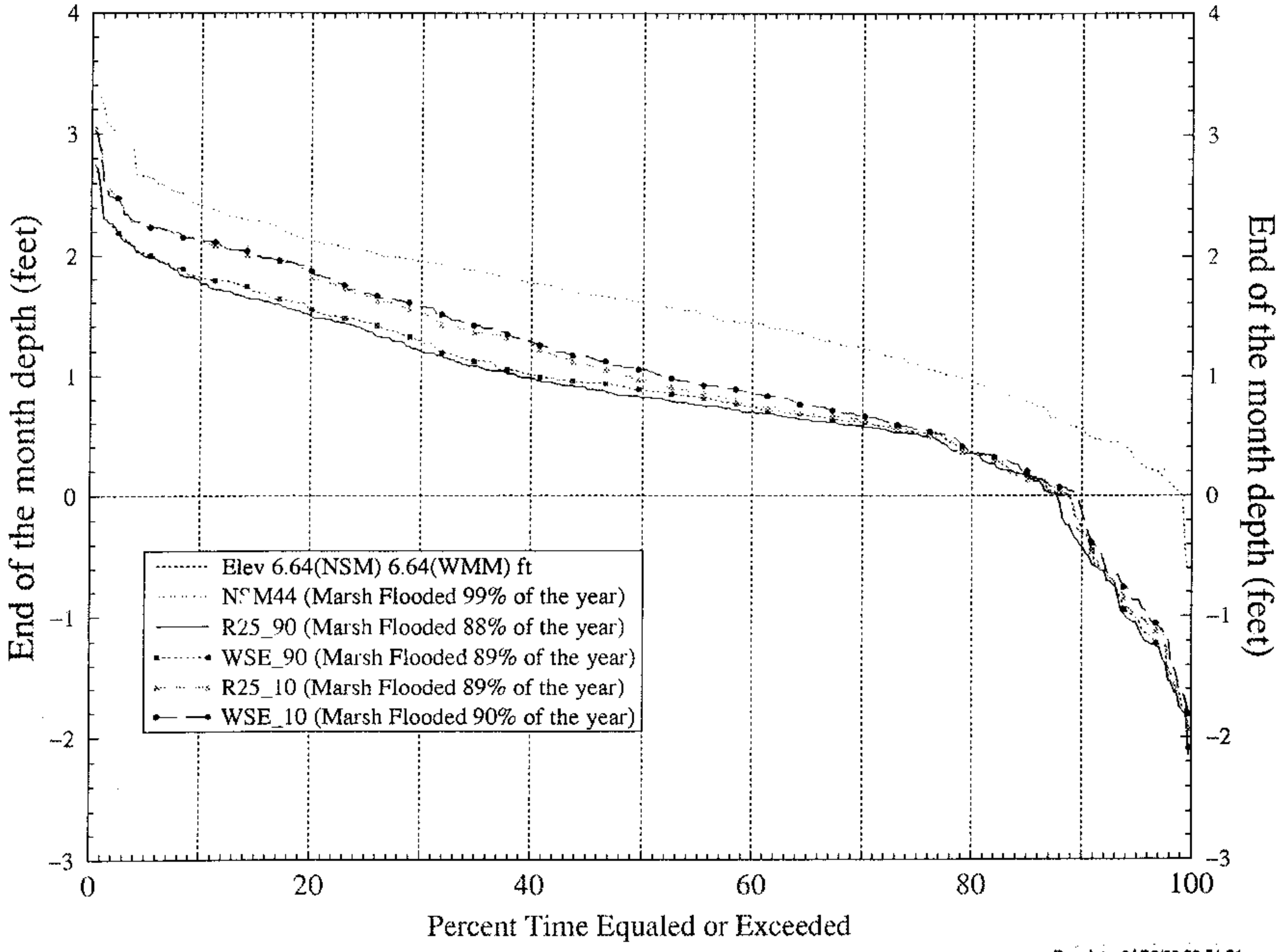
Normalized Stage Hydrograph at Cell (R24 C25)
South End of WCA-3B



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 04/28/98 09:51:32
For Planning Purposes Only
SFWMM V3.2

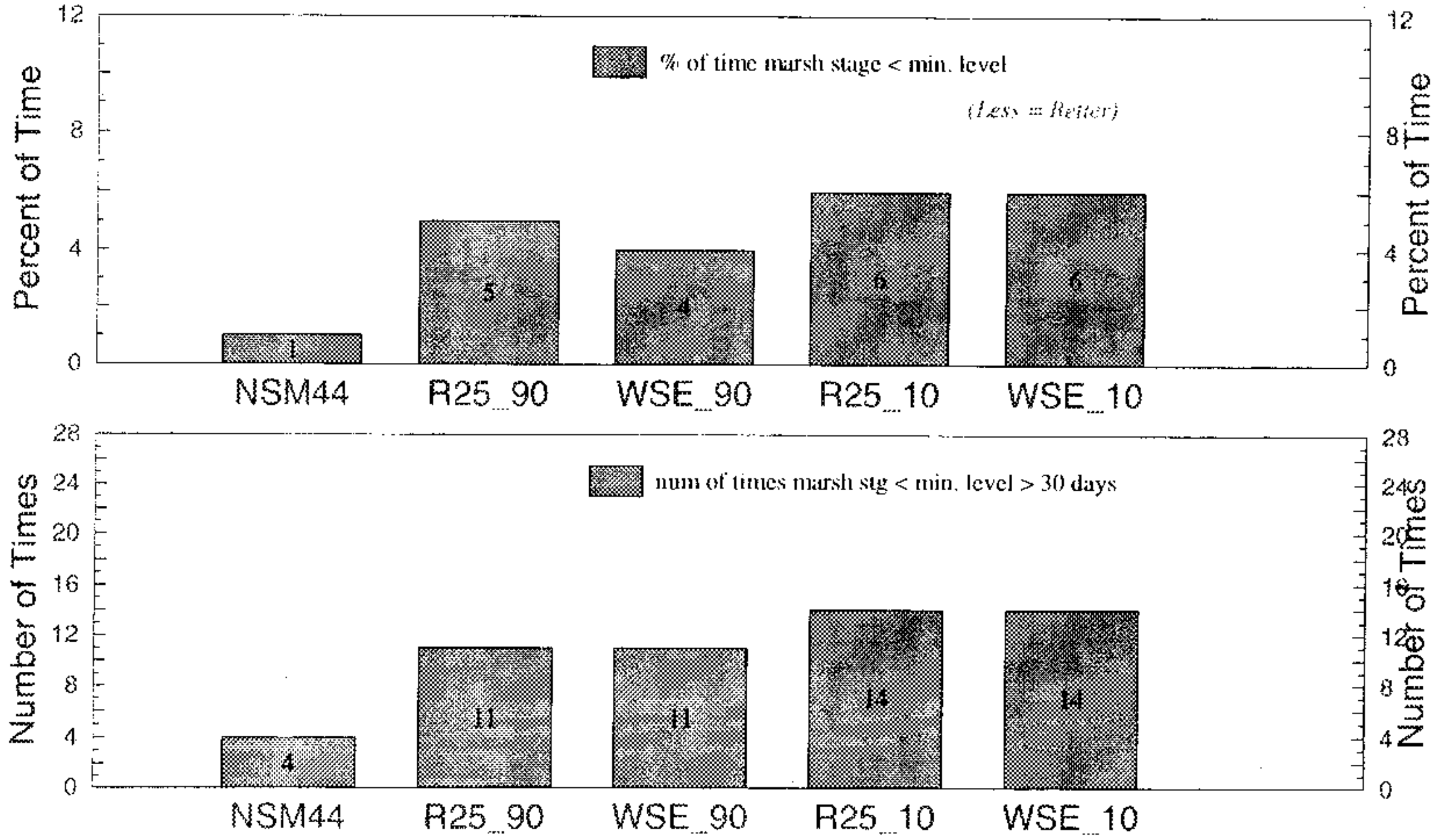
Normalized Stage Duration Curves at Cell (R24 C25)
South End of WCA–3B



Run date: 04/28/98 09:51:21
For Planning Purposes Only

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

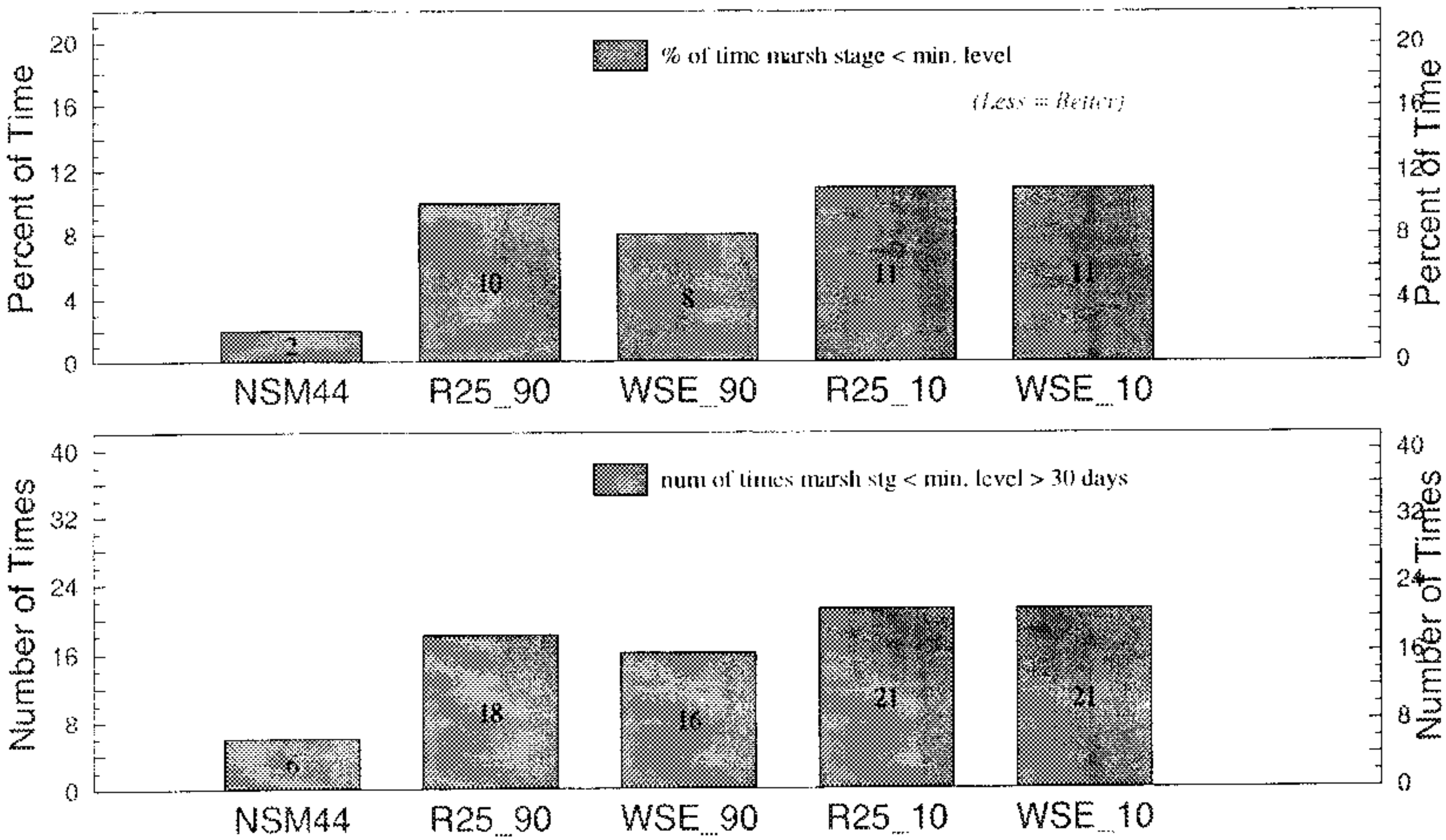
% of Time Marsh Stage < Minimum Level Criteria and Occurences* > 30 days (Gage 2–17, Cell R40 C29, Proposed Min Lvl 1 ft below ground)



*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 04/24/98 13:28:28
For Planning Purposes Only
SFWMM V3.2

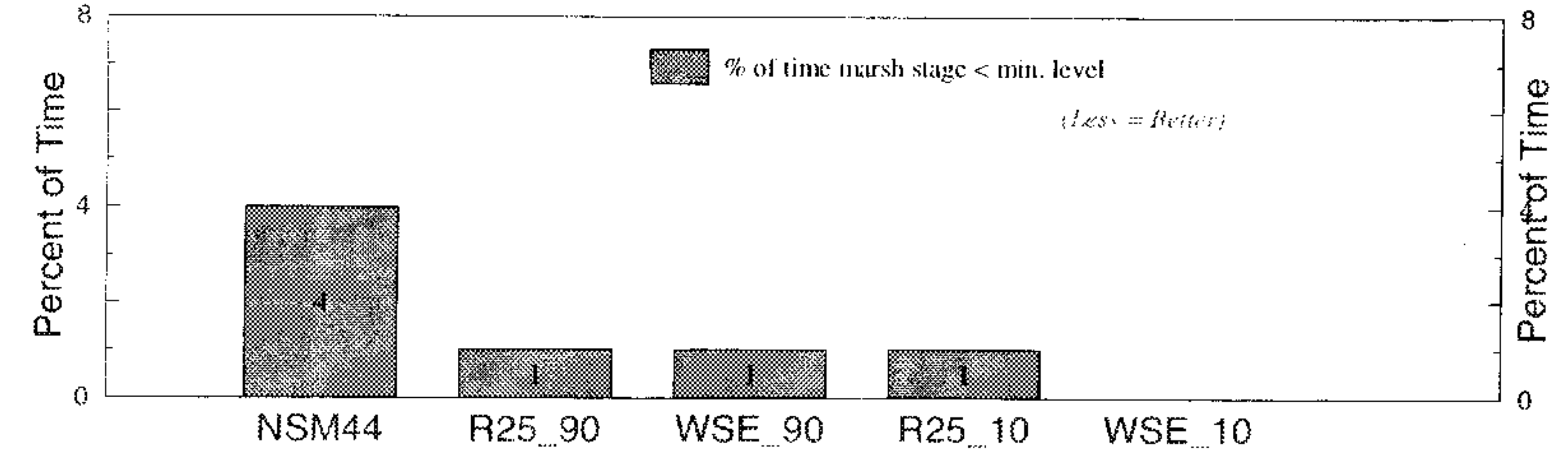
% of Time Marsh Stage < Minimum Level Criteria and Occurences* > 30 days
(Gage 3A-2, Cell R36 C18, Proposed Min Lvl 1 ft below ground)

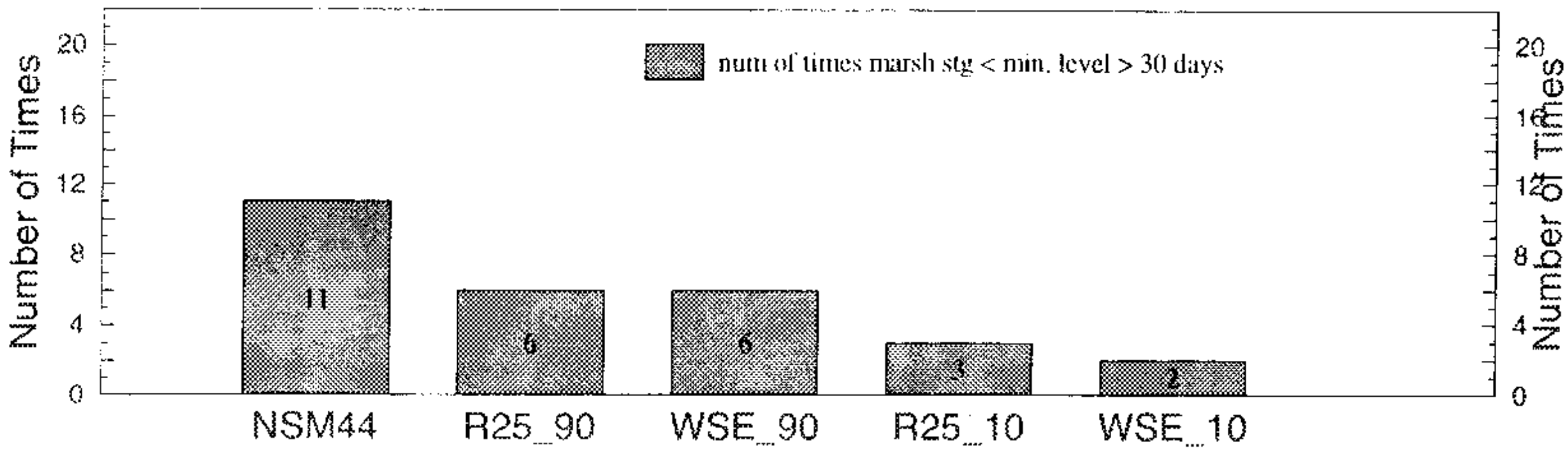


*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 04/24/98 13:29:54
For Planning Purposes Only
SFWMM V3.2

% of Time Marsh Stage < Minimum Level Criteria and Occurences* > 30 days
Gage 3A–3, Cell R37 C25, Proposed Min Lvl 1 ft below ground

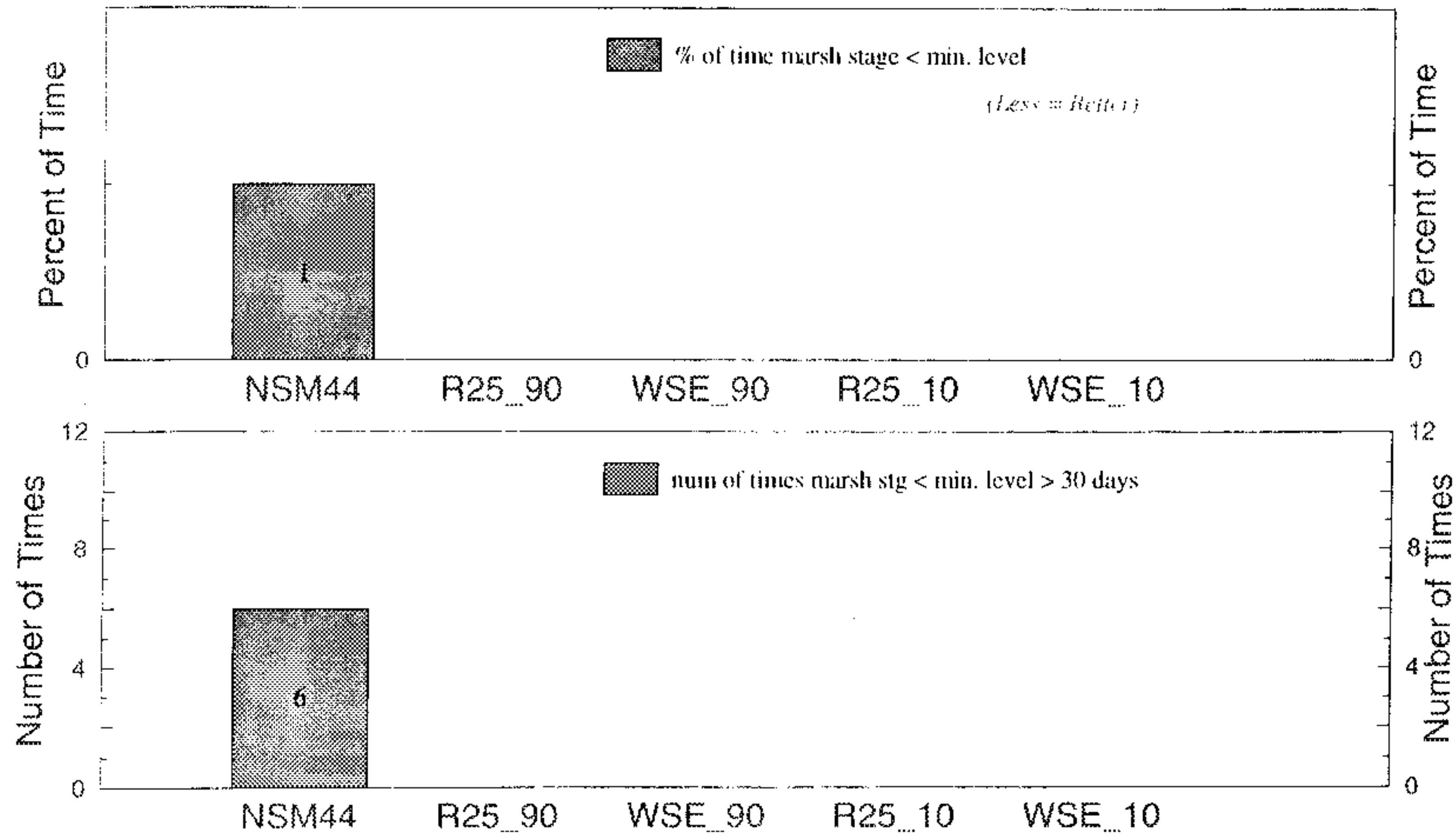




*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 04/24/98 13:21:25
For Planning Purposes Only
SFWMM V3.2

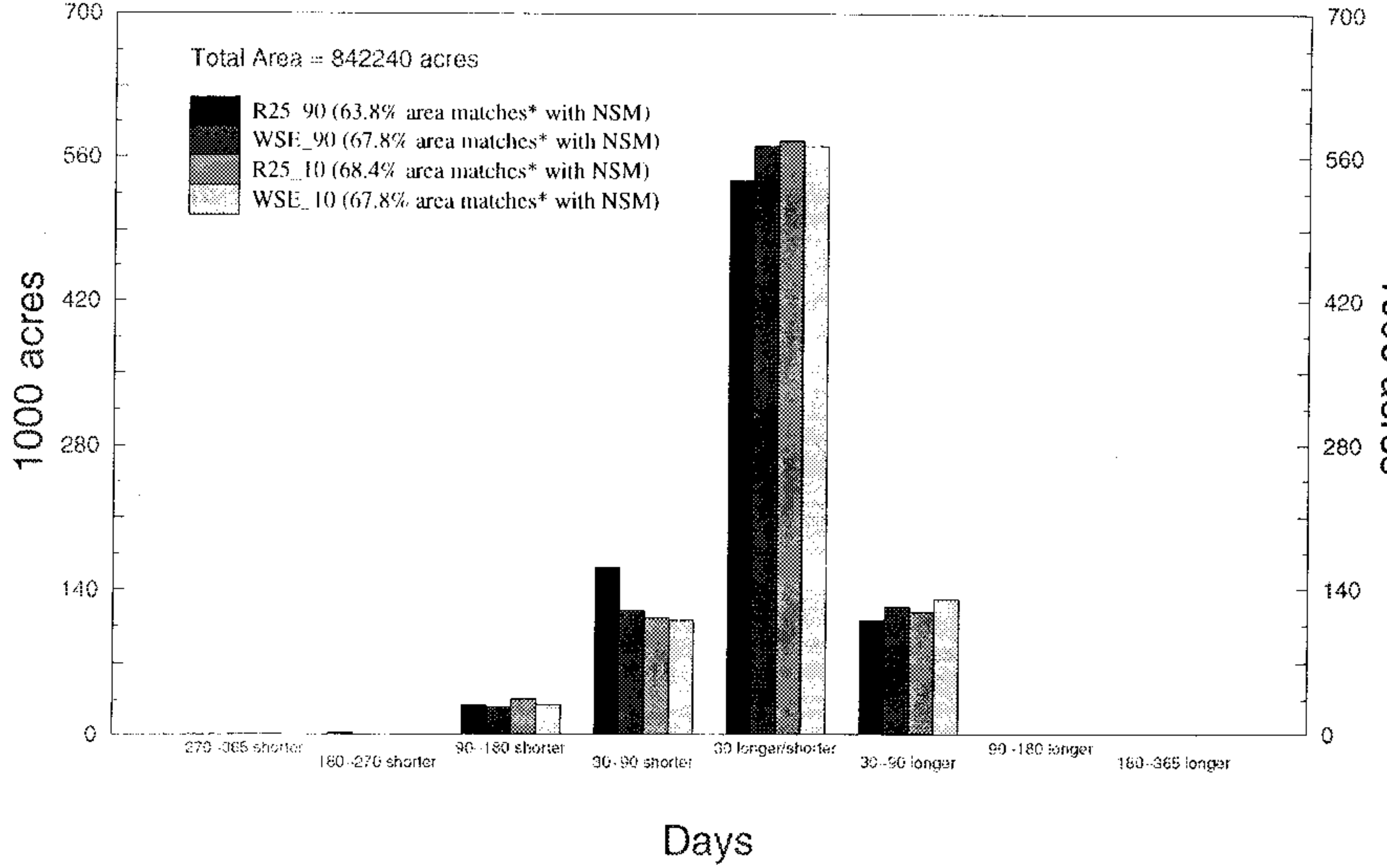
% of Time Marsh Stage < Minimum Level Criteria and Occurences* > 30 days (Gage 3A–28, Cell R24 C19, Proposed Min Lvl 1 ft below ground)



*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 04/24/98 12:28:42
For Planning Purposes Only
SFWMM V3.2

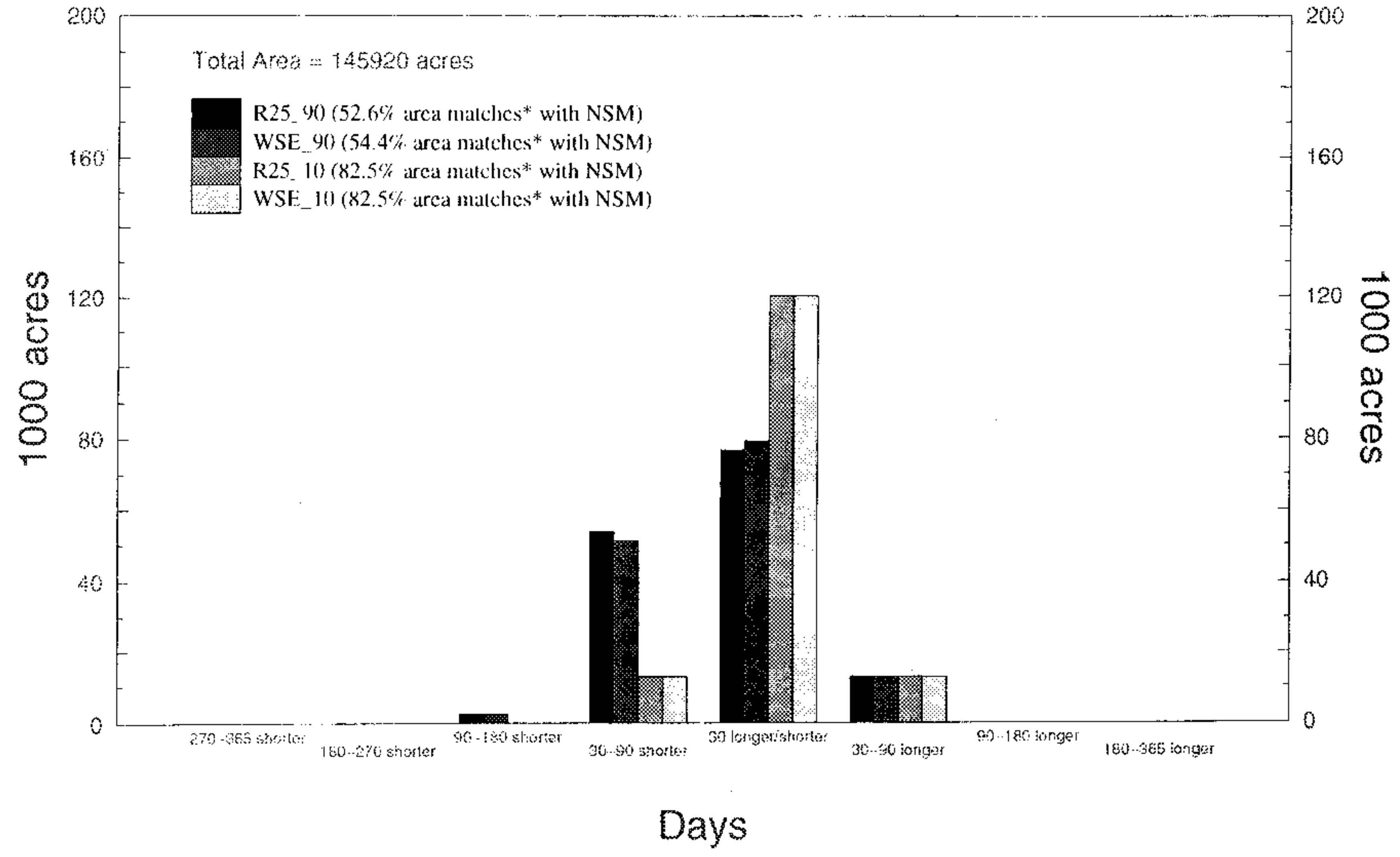
Mean NSM hydroperiod matches for the WCA SYSTEM for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 04/24/98 12:10:13
For Planning Purposes Only
SFWMM V3.2

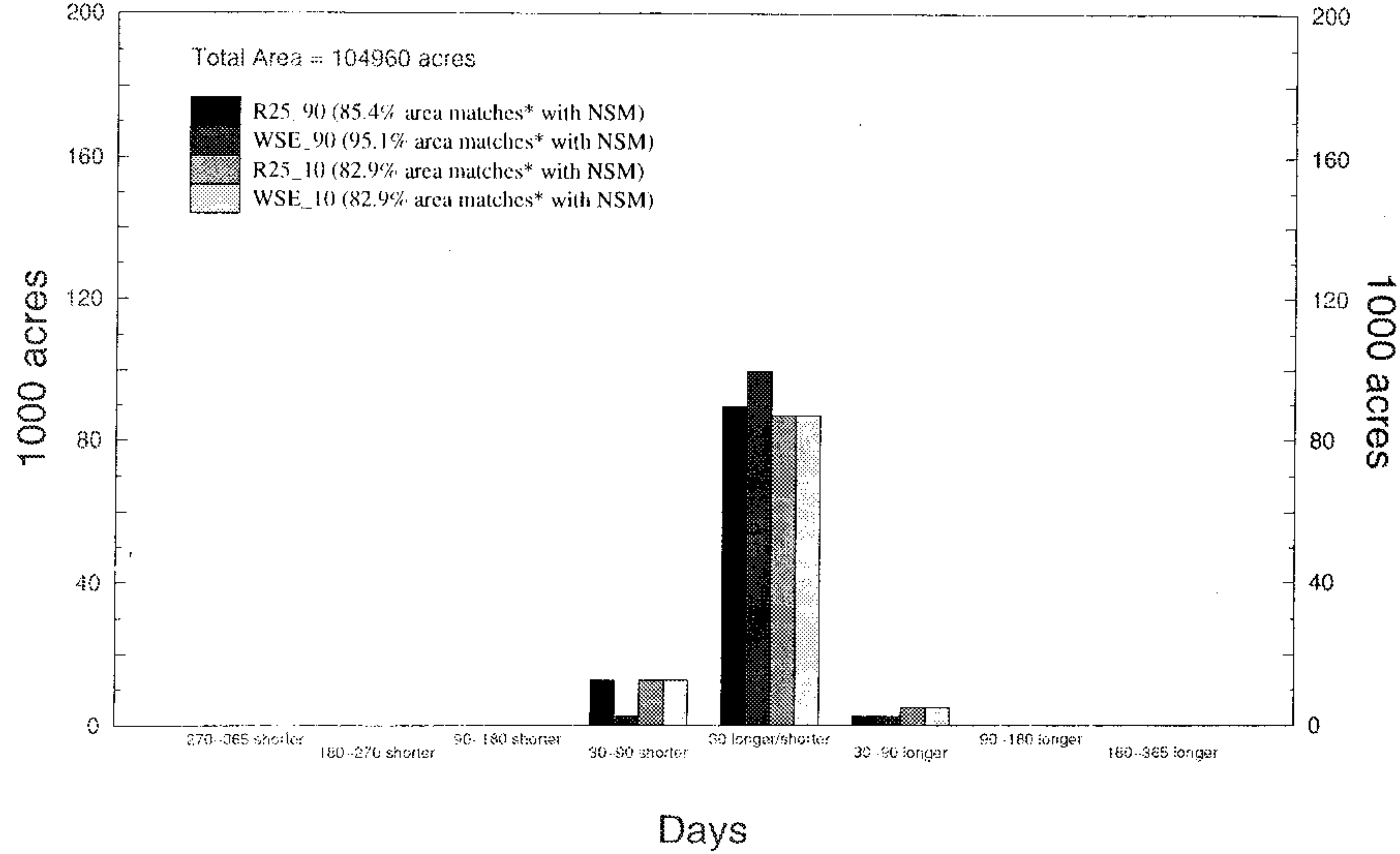
Mean NSM hydroperiod matches for WCA–1 for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM

Run date: 04/24/98 12:09:20
For Planning Purposes Only

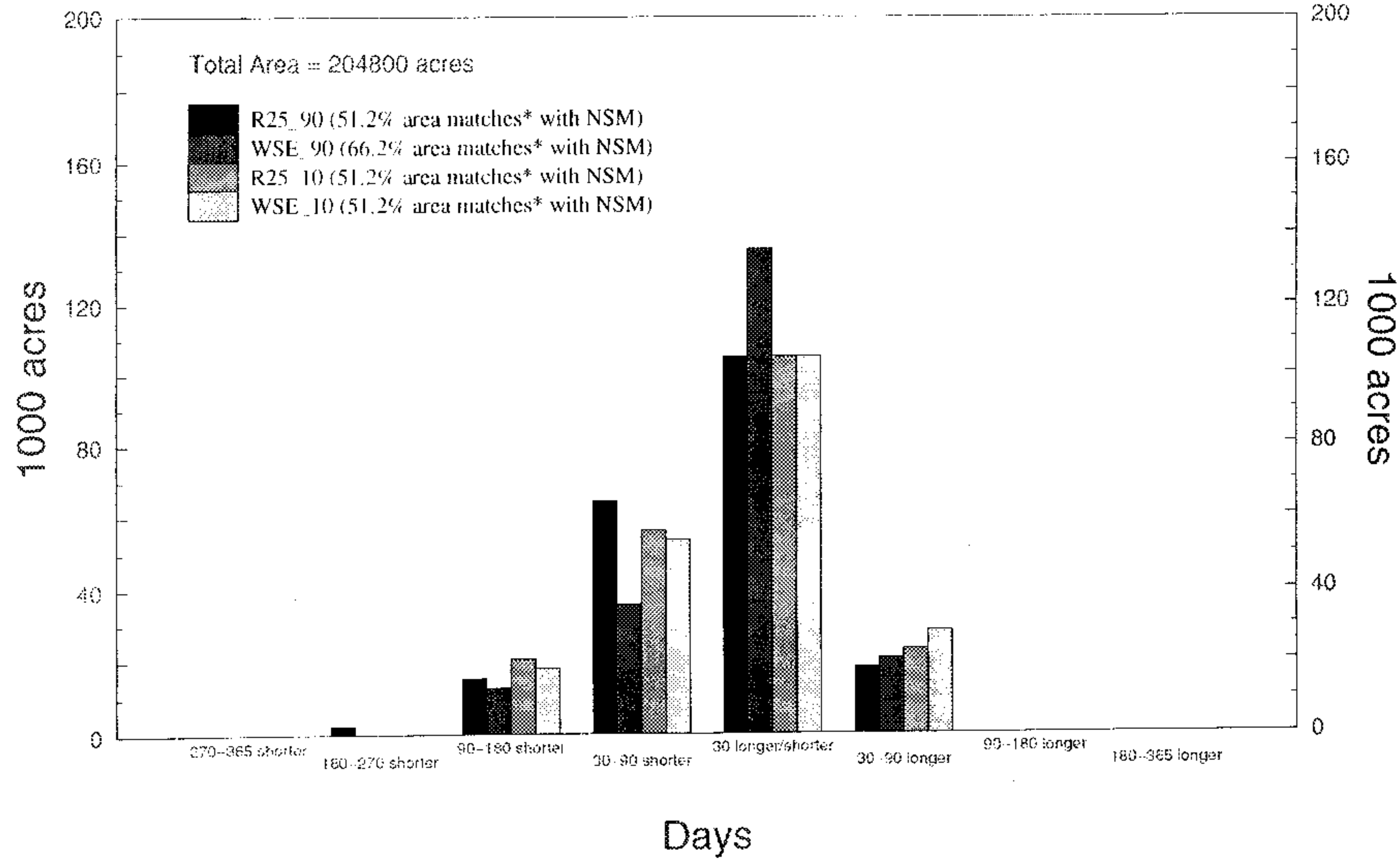
Mean NSM hydroperiod matches for WCA–2A for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 04/24/98 12:09:27
For Planning Purposes Only
SFWMM V3.2

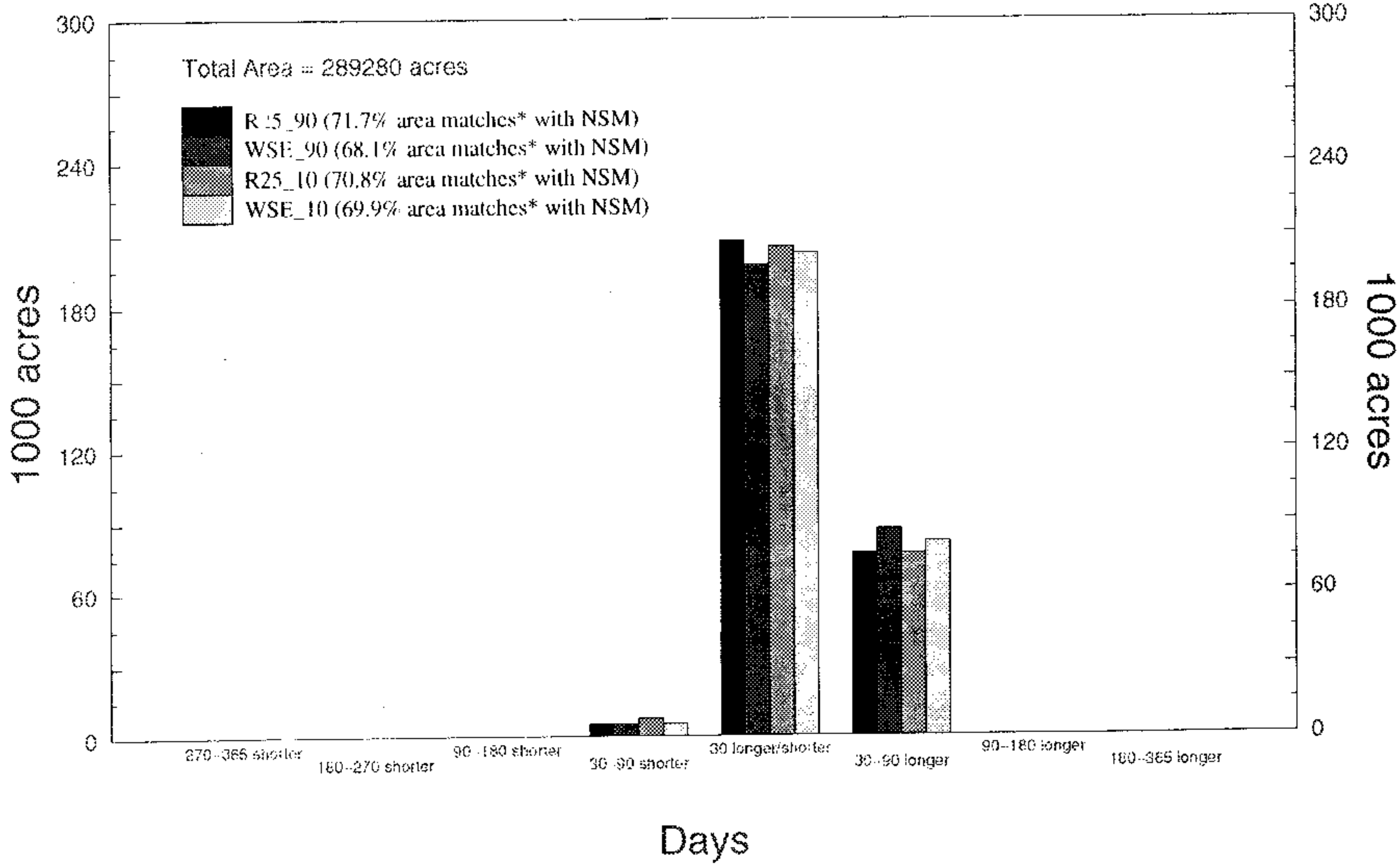
Mean NSM hydroperiod matches for WCA-3A(North) for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM

Run date: 04/24/98 12:09:41
For Planning Purposes Only

Mean NSM hydroperiod matches for WCA–3A(South) for the 31 yr. simulation



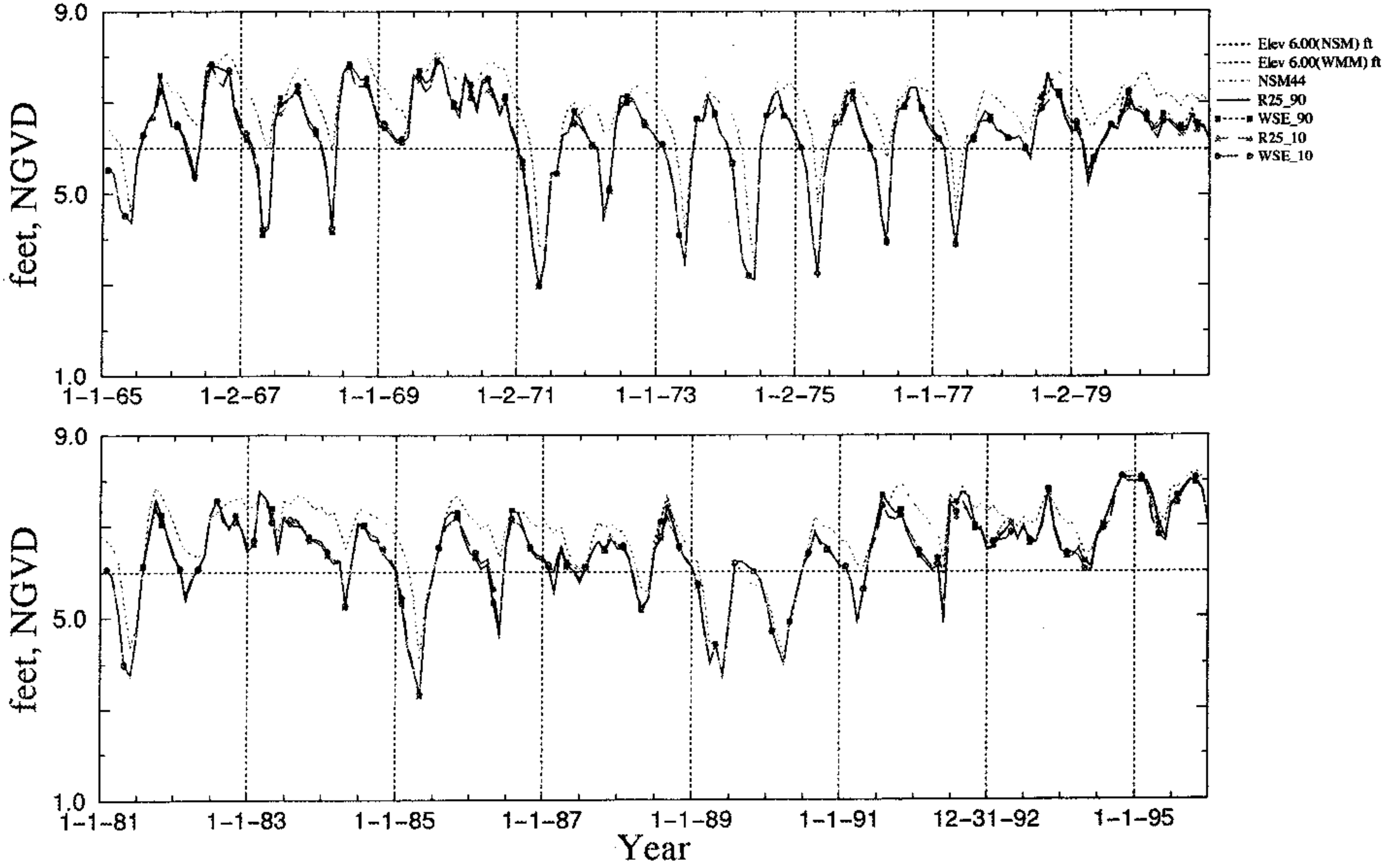
Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 04/24/98 12:09:49
For Planning Purposes Only
SFWMM V3.2

Performance Measures for

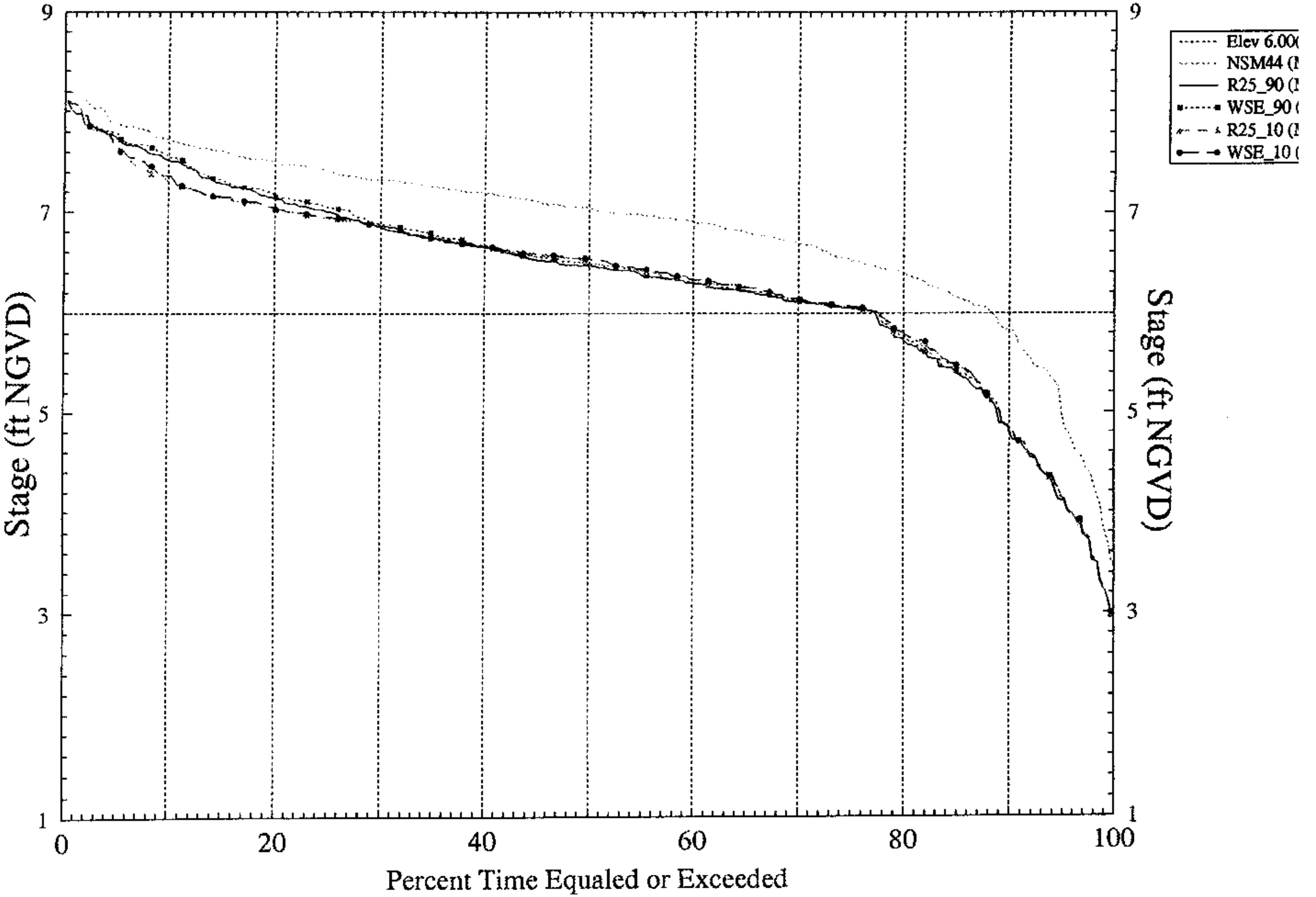
Everglades National Park

Stage Hydrograph for Marl Lands in NW SRS
Gage G–620, ENP, Cell R19 C18



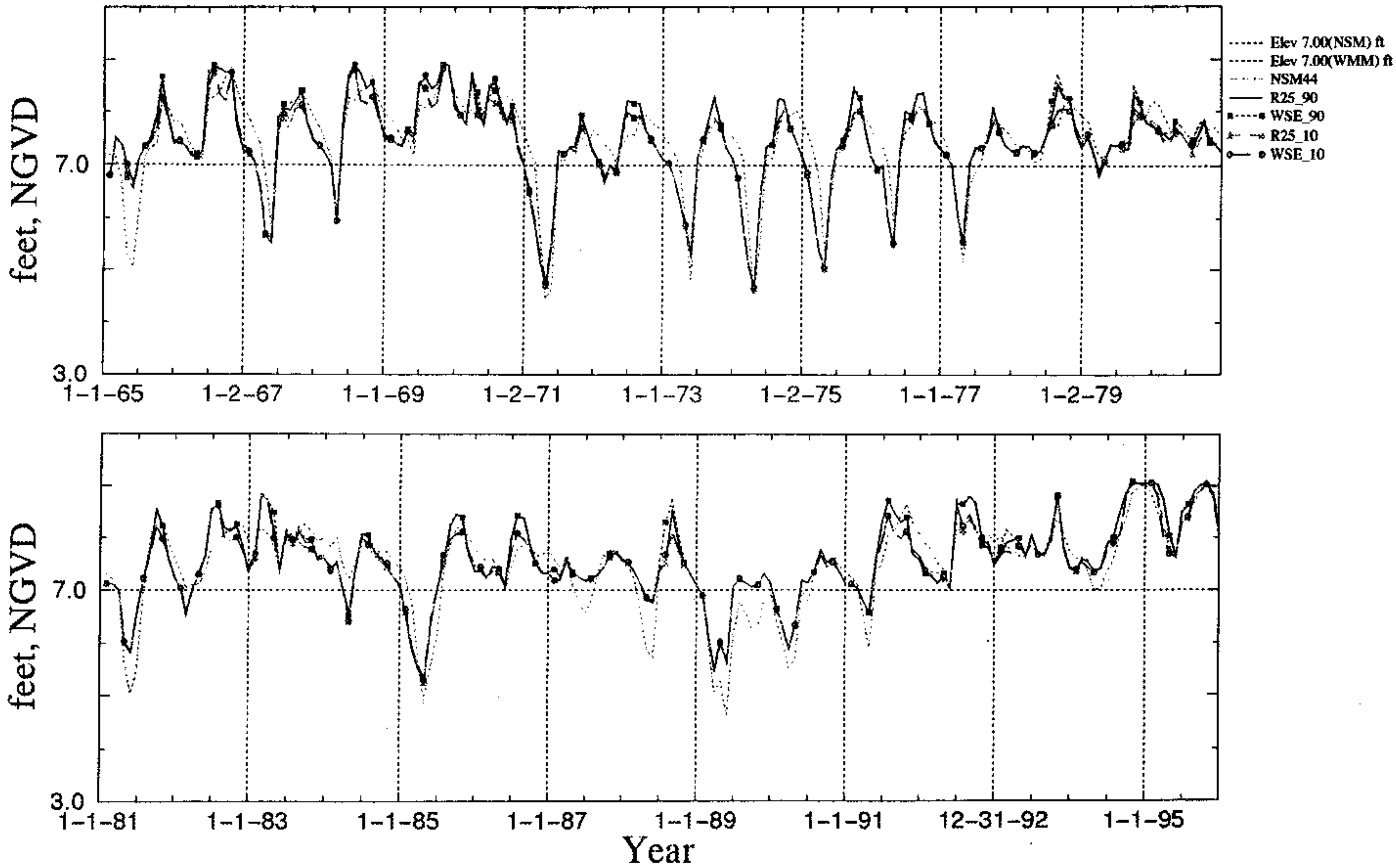
Run date: 04/24/98 12:21:21
For Planning Purposes Only
SFWMM V3.2

Stage Duration Curves for Marl Lands in NW SRS
Gage G-620, ENP, Cell R19 C18



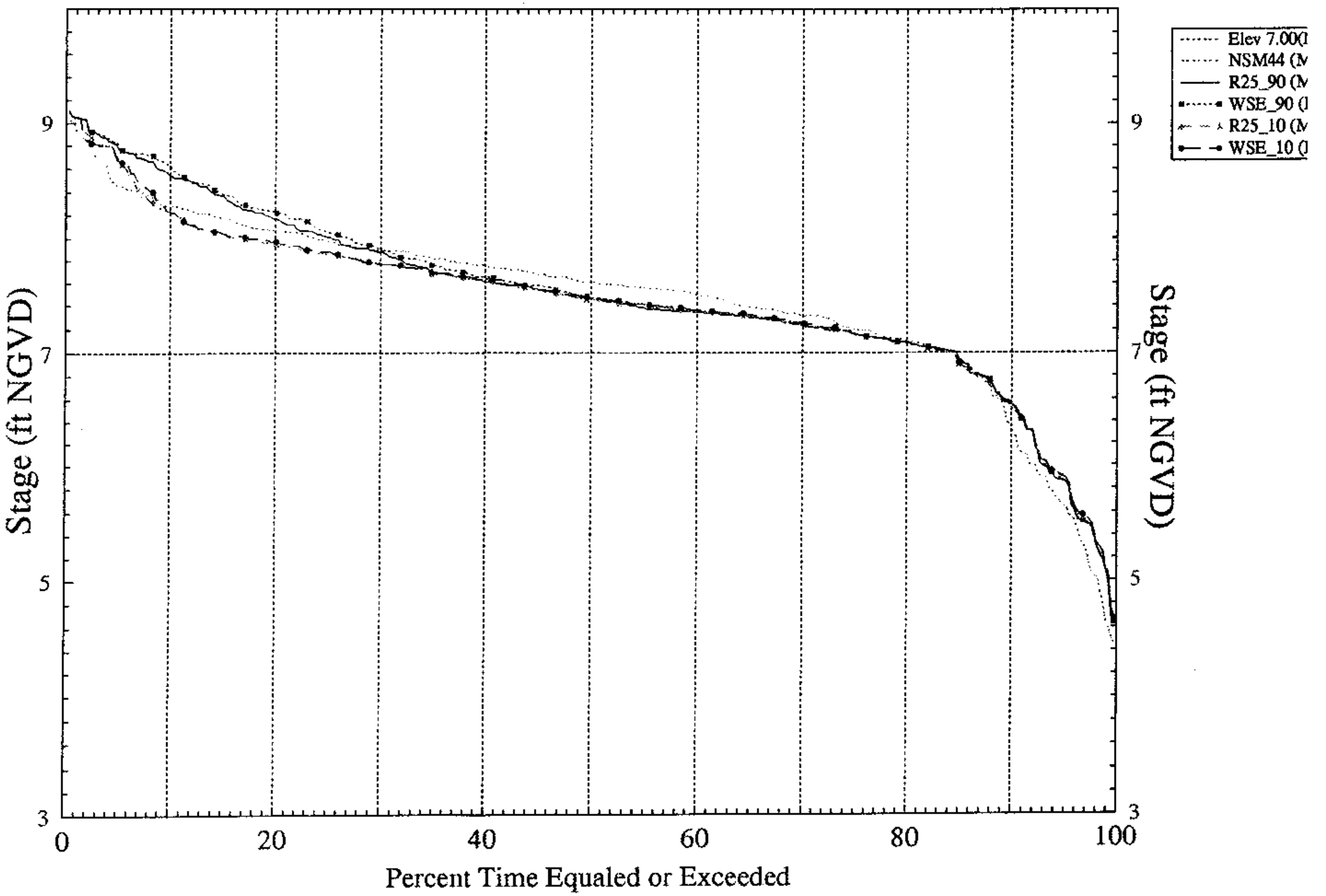
Run date: 04/24/98 12:18:54
For Planning Purposes Only

Stage Hydrograph at Northern Shark River Slough
Gage NP–201, Cell R21 C19



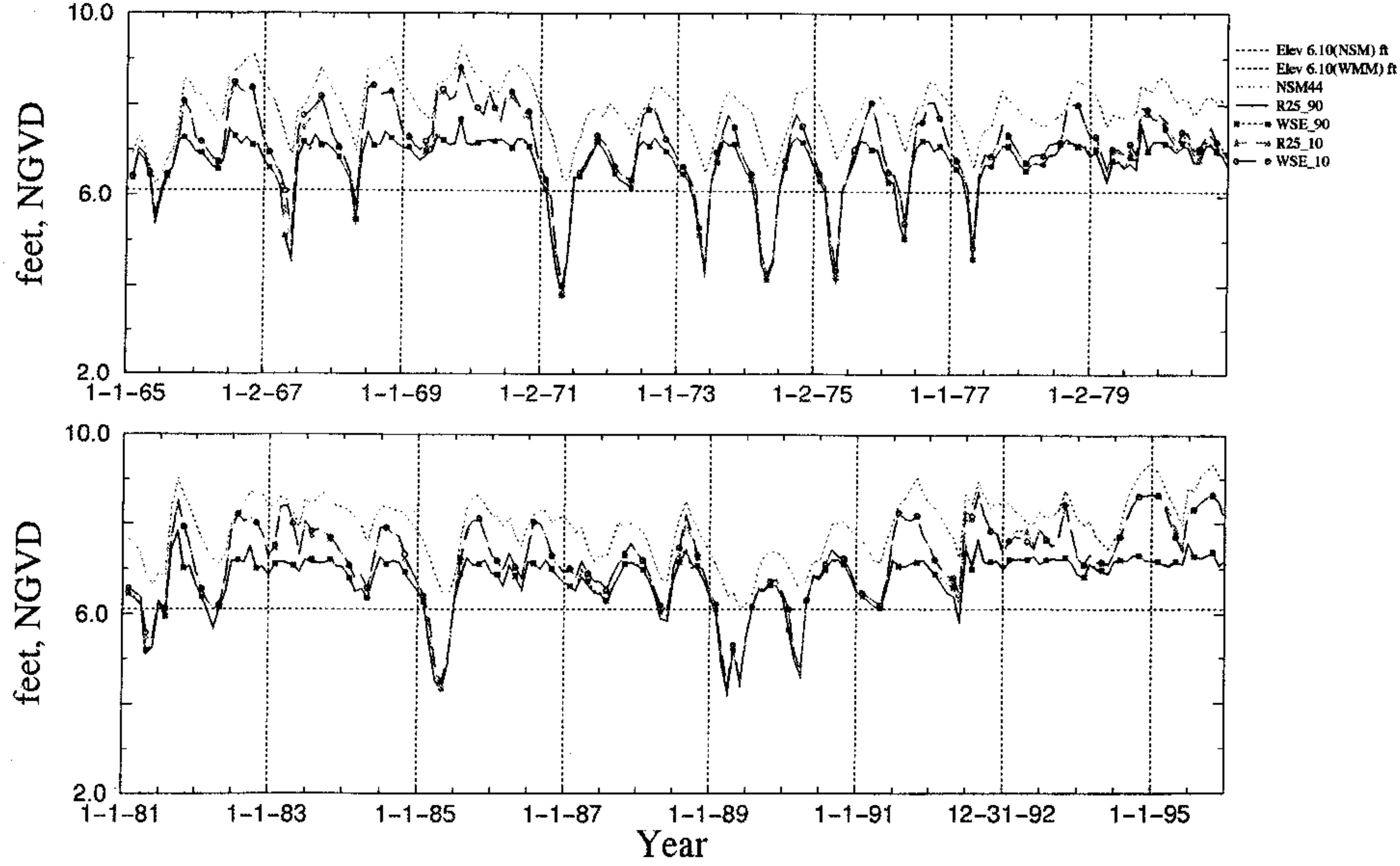
Run date: 04/24/98 12:19:29
For Planning Purposes Only
SFWMM V3.2

Stage Duration Curves at Northern Shark River Slough
Gage NP-201, Cell R21 C19



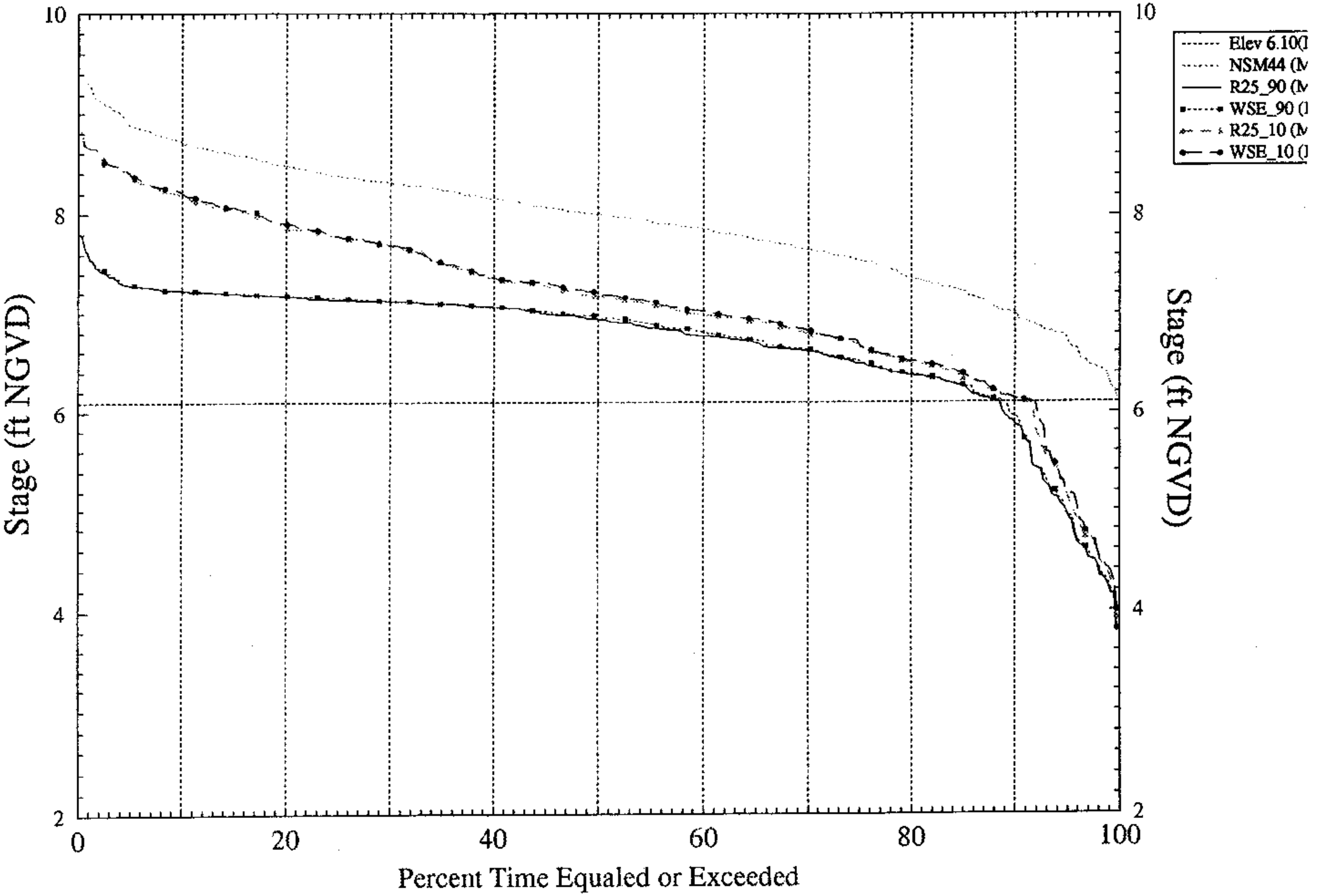
Run date: 04/24/98 12:17:12
For Planning Purposes Only

Stage Hydrograph at N.E. Shark River Slough
Gage NESRS-2, Cell R21 C24



Run date: 04/24/98 12:19:46
For Planning Purposes Only
SFWMM V3.2

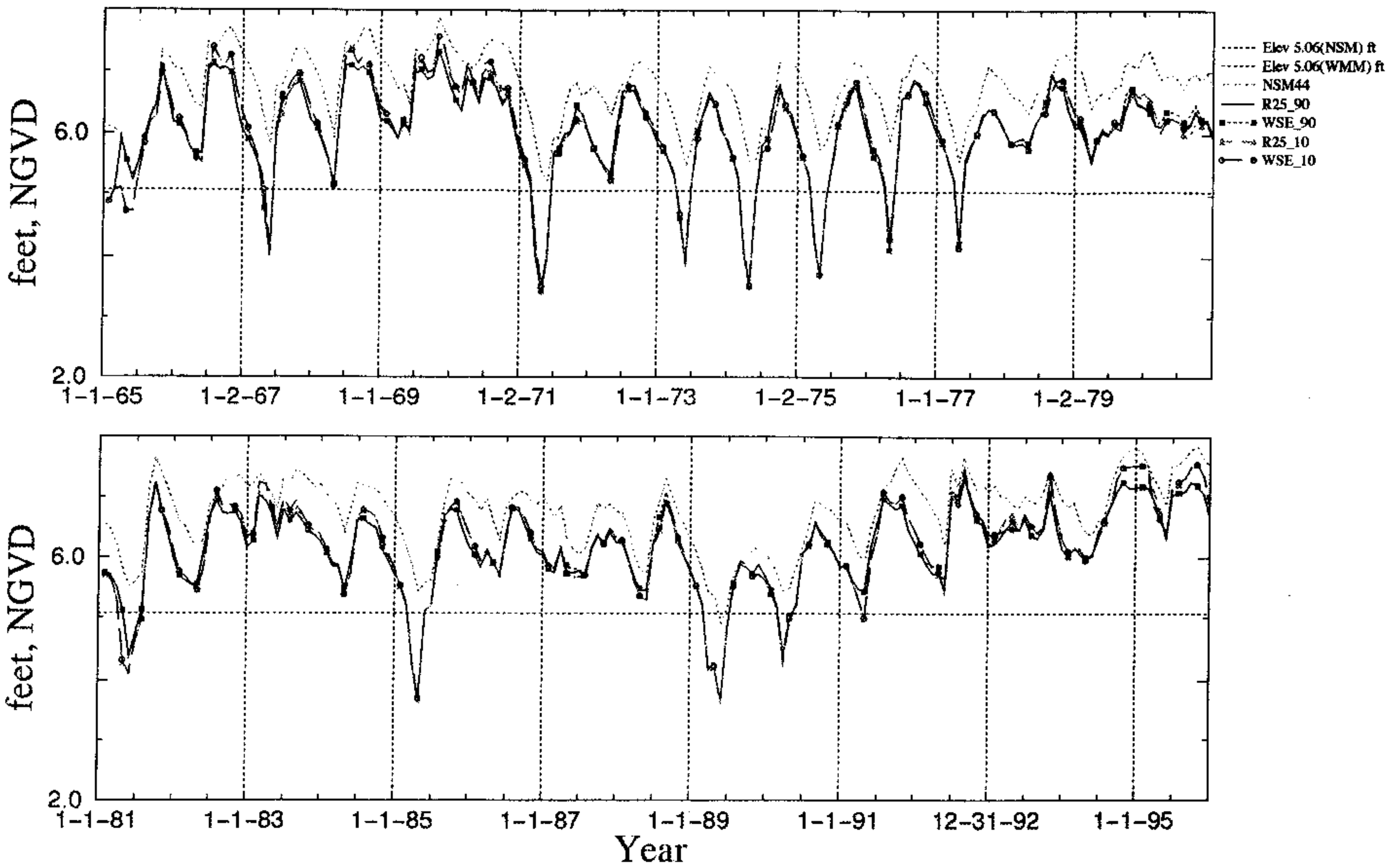
Stage Duration Curves at N.E. Shark River Slough
Gage NESRS-2, Cell R21 C24



Run date: 04/24/98 12:17:22
For Planning Purposes Only

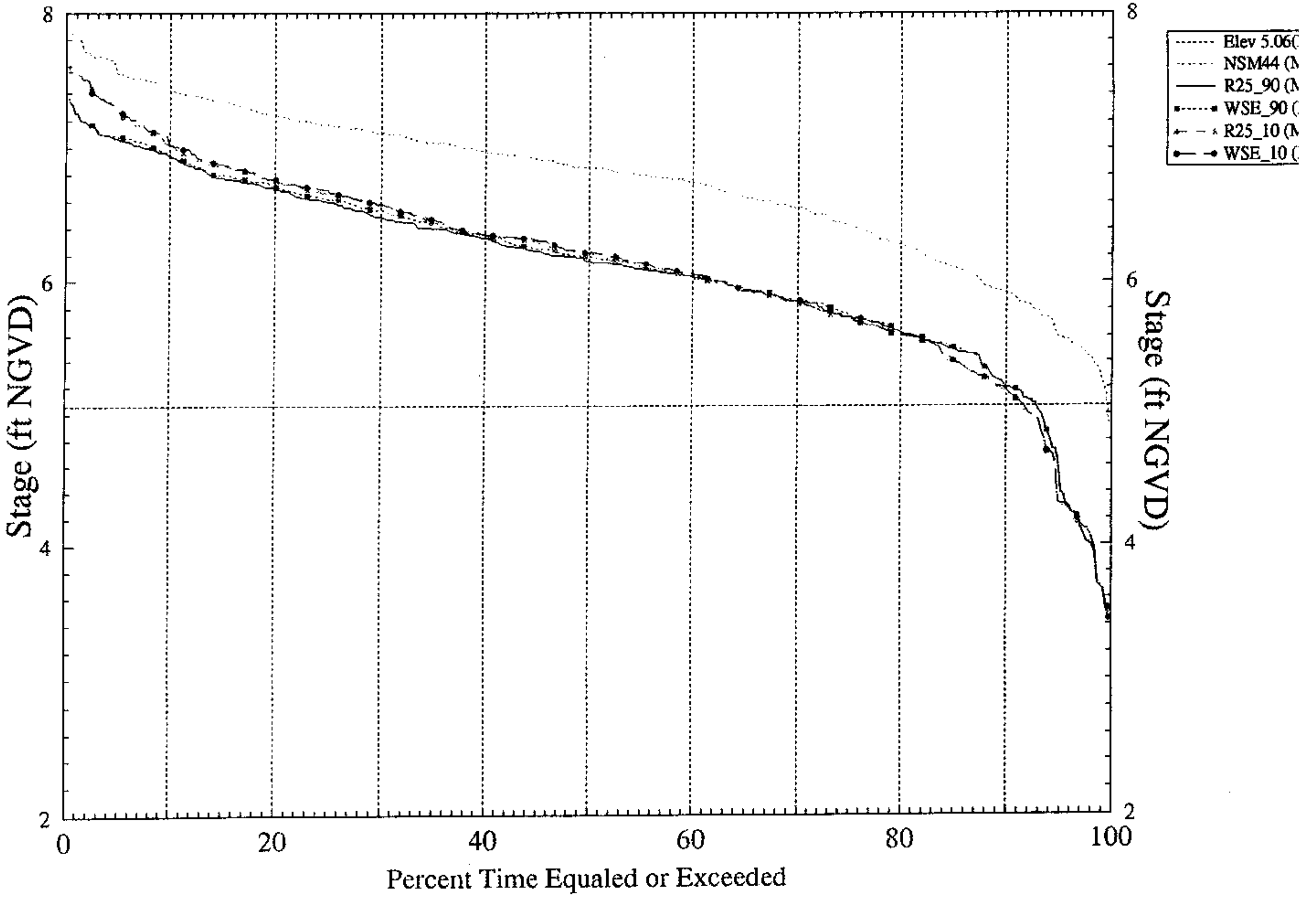
E-50

Stage Hydrograph at Everglades National Park
Gage NP–33, Cell R17 C20



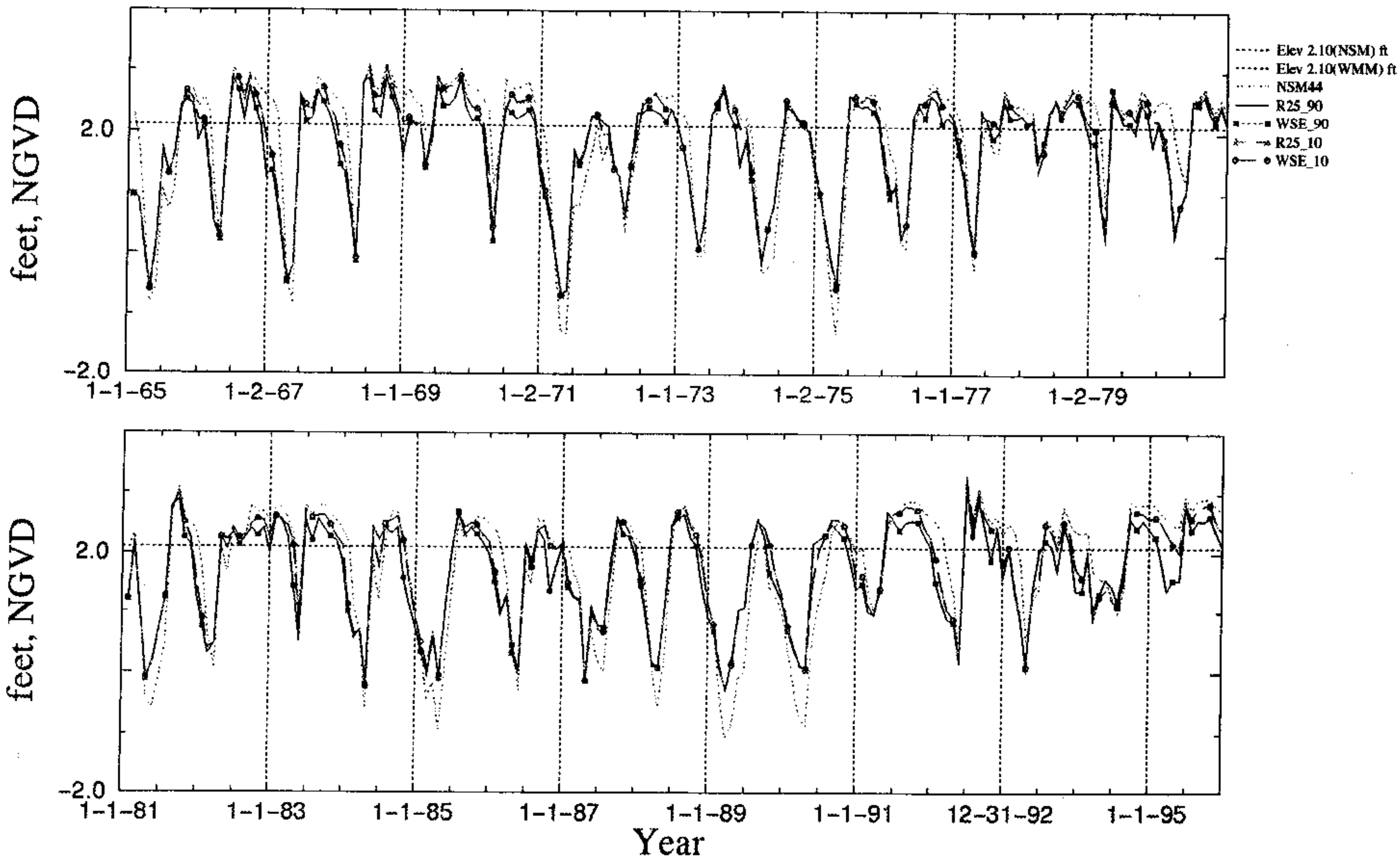
Run date: 04/24/98 12:20:19
For Planning Purposes Only
SFWMM V3.2

Stage Duration Curves at Everglades National Park
Gage NP–33, Cell R17 C20



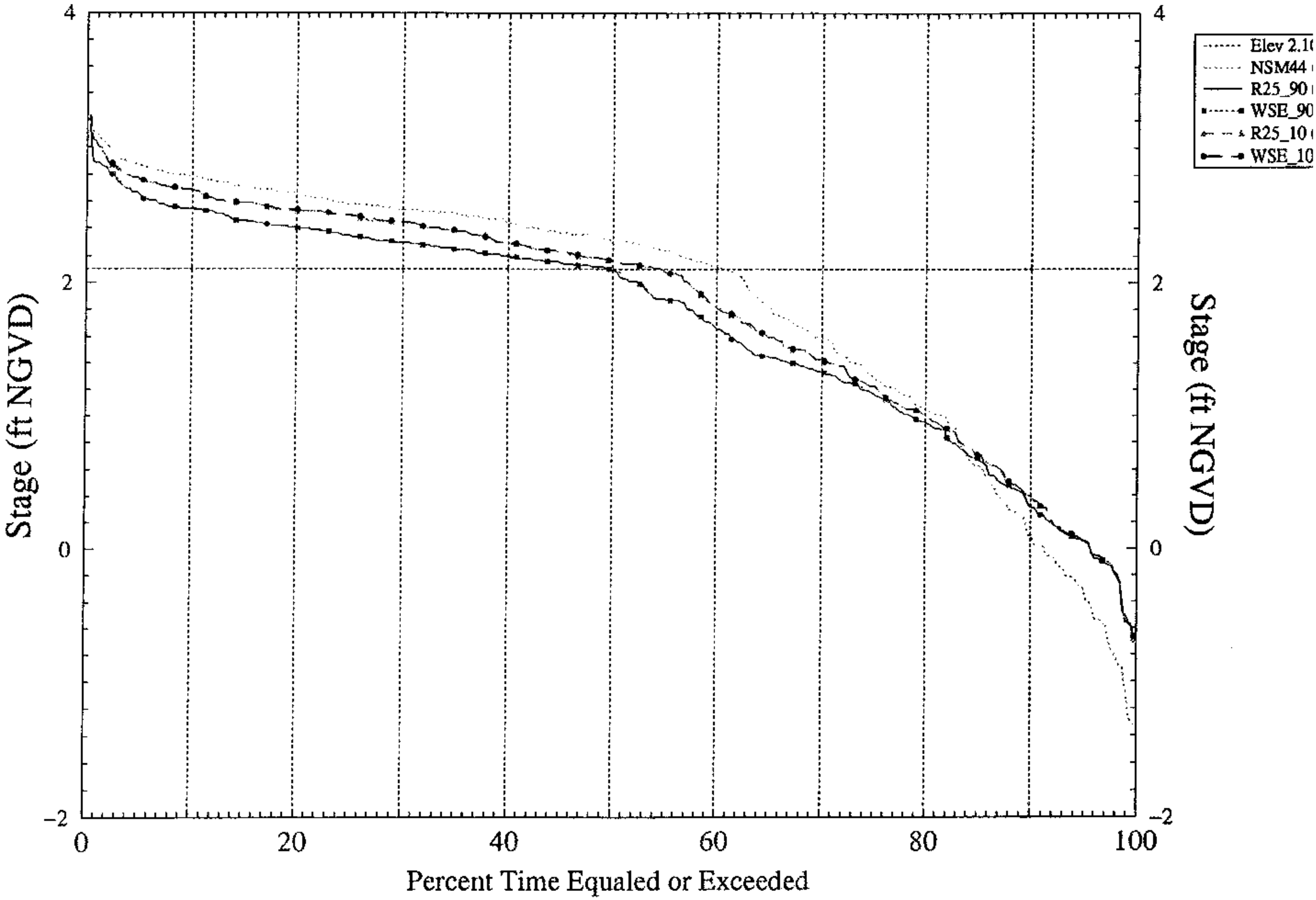
Run date: 04/24/98 12:17:47
For Planning Purposes Only

Stage Hydrograph at C-111 Basin
Gage G-1251, Cell R7 C24



Run date: 04/24/98 12:20:40
For Planning Purposes Only
SFWMM V3.2

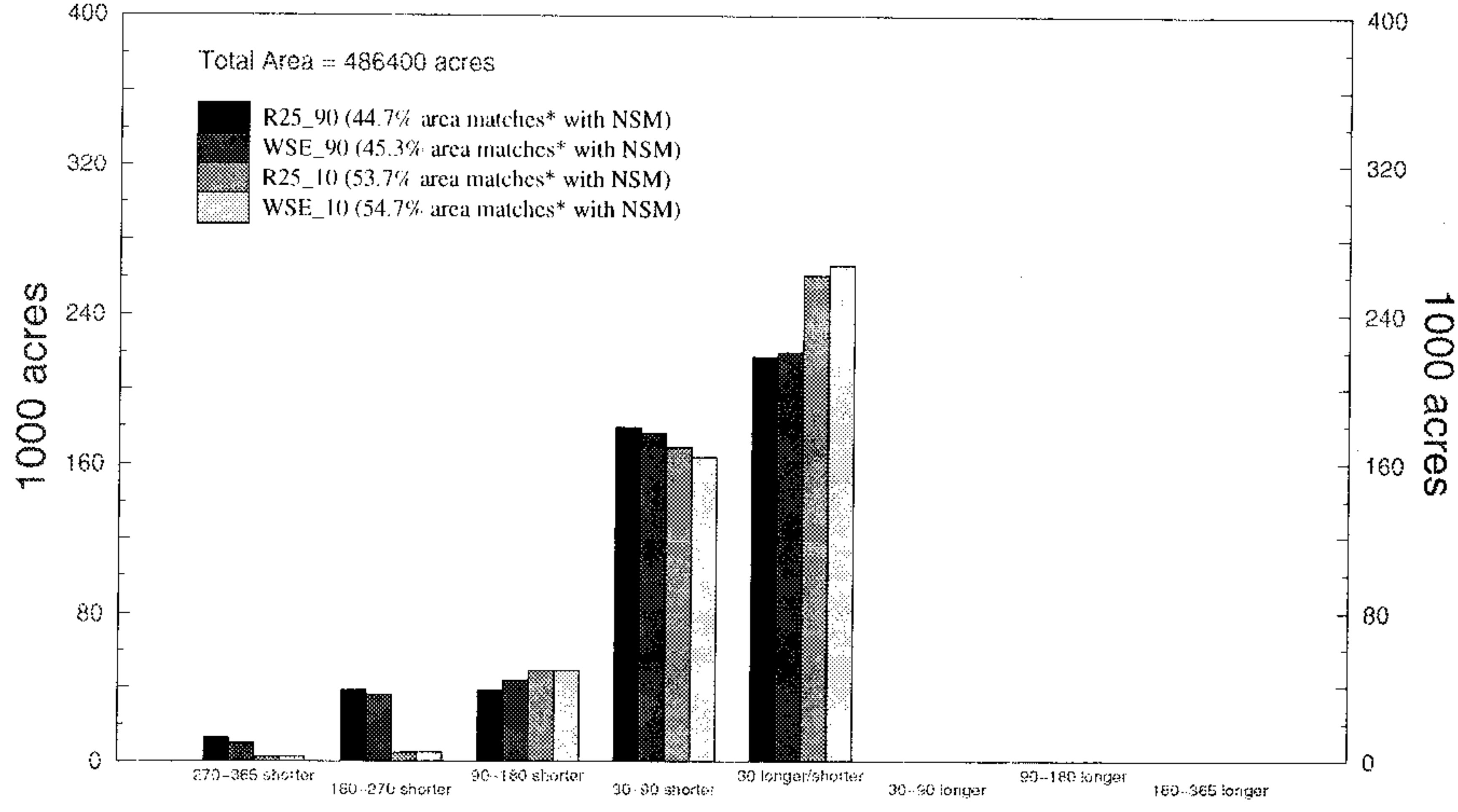
Stage Duration Curves at C–111 Basin
Gage G–1251, Cell R7 C24



Run date: 04/24/98 12:18:13
For Planning Purposes Only

E-54

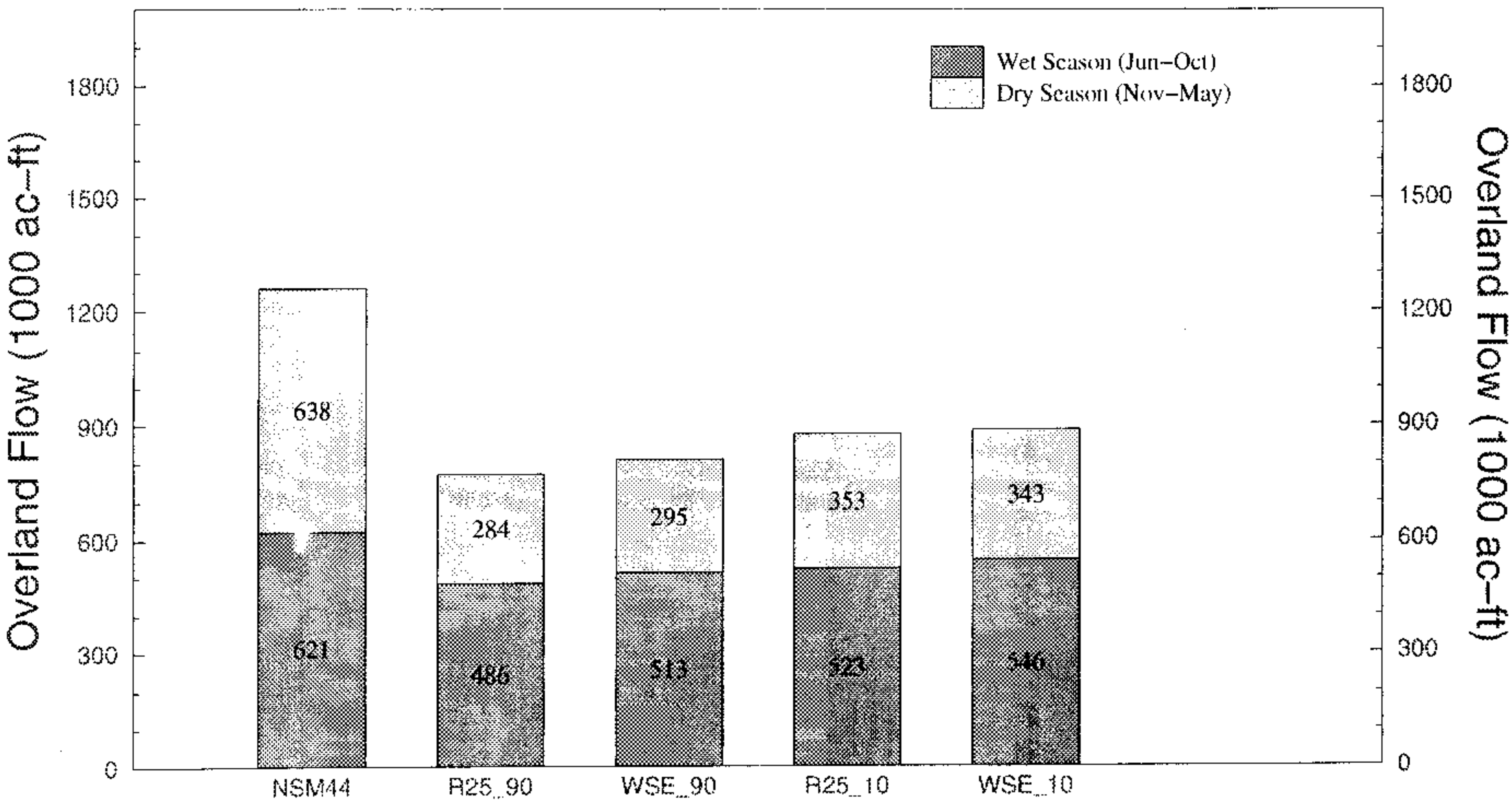
Mean NSM hydroperiod matches for the Everglades National Park for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 04/24/98 12:10:02
For Planning Purposes Only
SFWMM V3.2

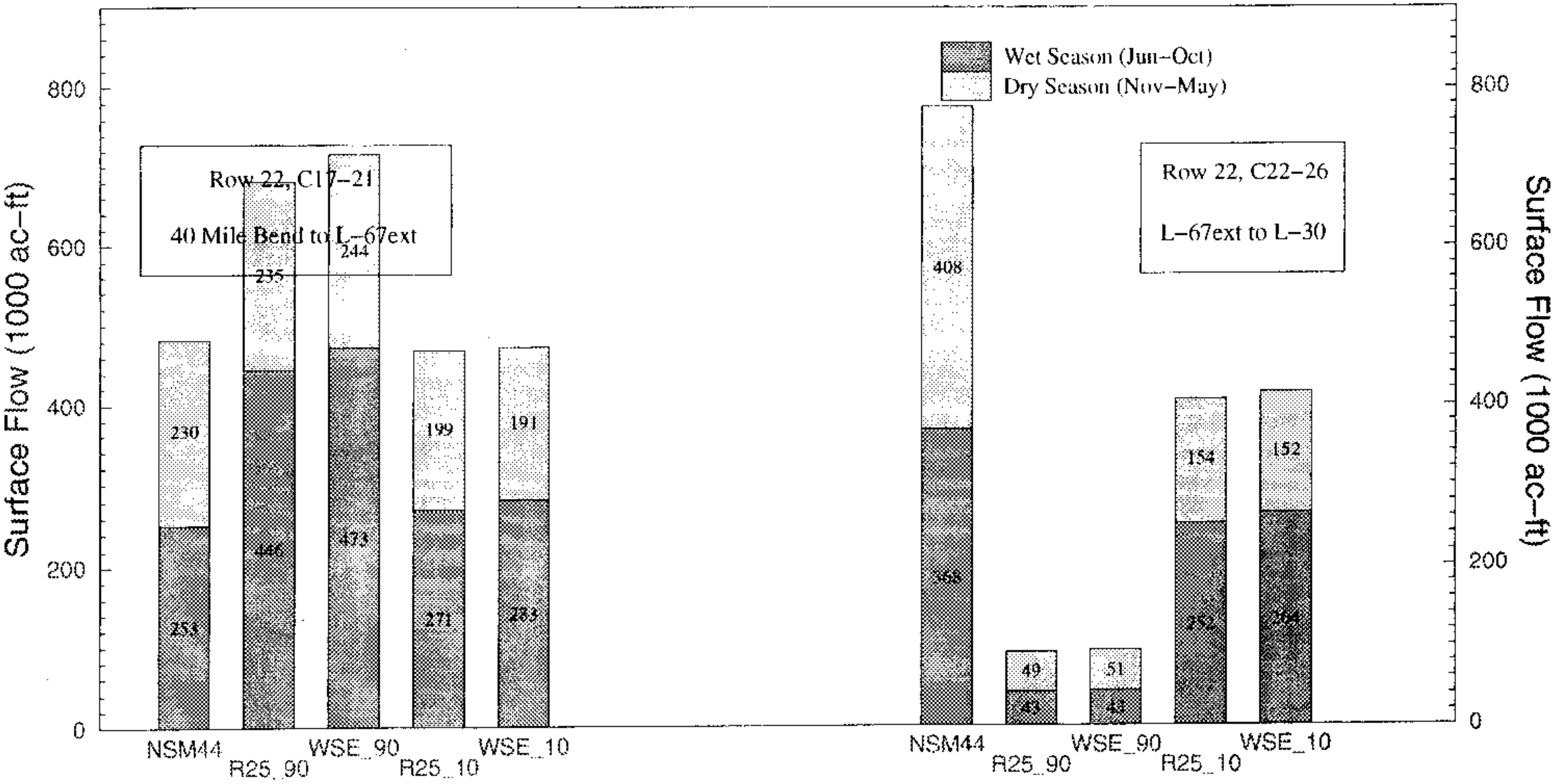
Wet/Dry Season Average Overland Flows South of Tamiami Trail to ENP for the 31 yr. simulation



Note: Flow represents overland flows for cells Row 22 Columns 17 thru 26. NSM water depths at key ENP gage locations are used as operational targets for most alternatives. NSM flows are NOT targets and are shown for comparative purposes only.

Run date: 04/24/98 12:08:31
For Planning Purposes Only

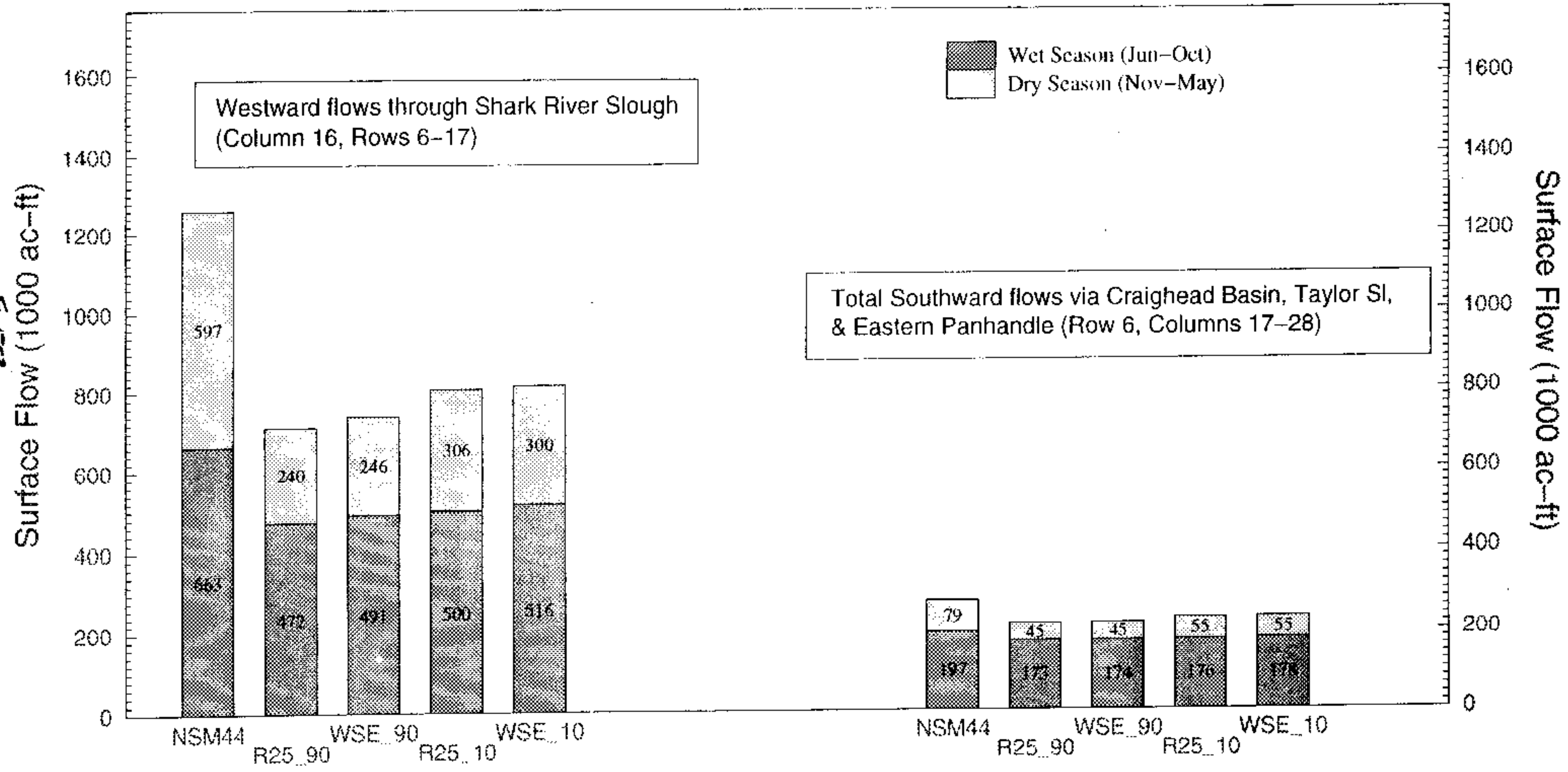
Average Annual Overland Flows to ENP South of Tamiami Trail, West & East of L–67ext for the 31 year simulation period



Note: Flow represents overland flows for cells Row 22 Columns 22 thru 26. NSM water depths at key ENP gage locations are used as operational targets for most alternatives. NSM flows are NOT targets and are shown for comparative purposes only.

Run date: 04/24/98 12:08:43
For Planning Purposes Only
SFWMM V3.2

Average Annual Overland Flows toward Whitewater Bay and Florida Bay for the 31 year simulation period



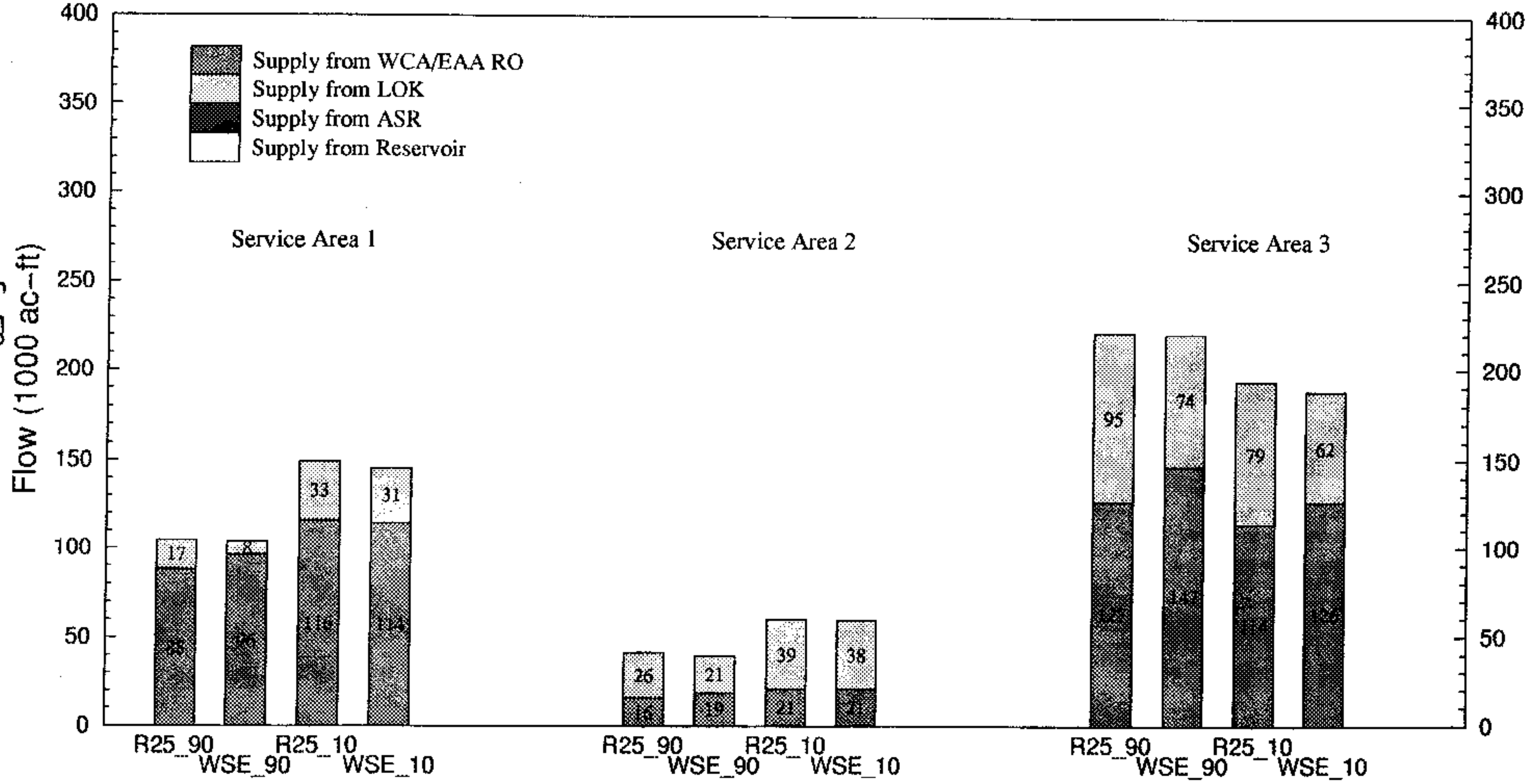
Note: NSM water depths at key ENP gage locations are used as operational targets for most alternatives.
NSM flows are NOT targets and are shown for comparative purposes only.

Run date: 04/24/98 12:08:57
For Planning Purposes Only

85-7
E-58

Performance Measures for the
Lower East Coast Service Areas

Mean Annual Regional System Water Supply Deliveries to LEC Service Areas for the five Drought years (71,75,81,85,89)



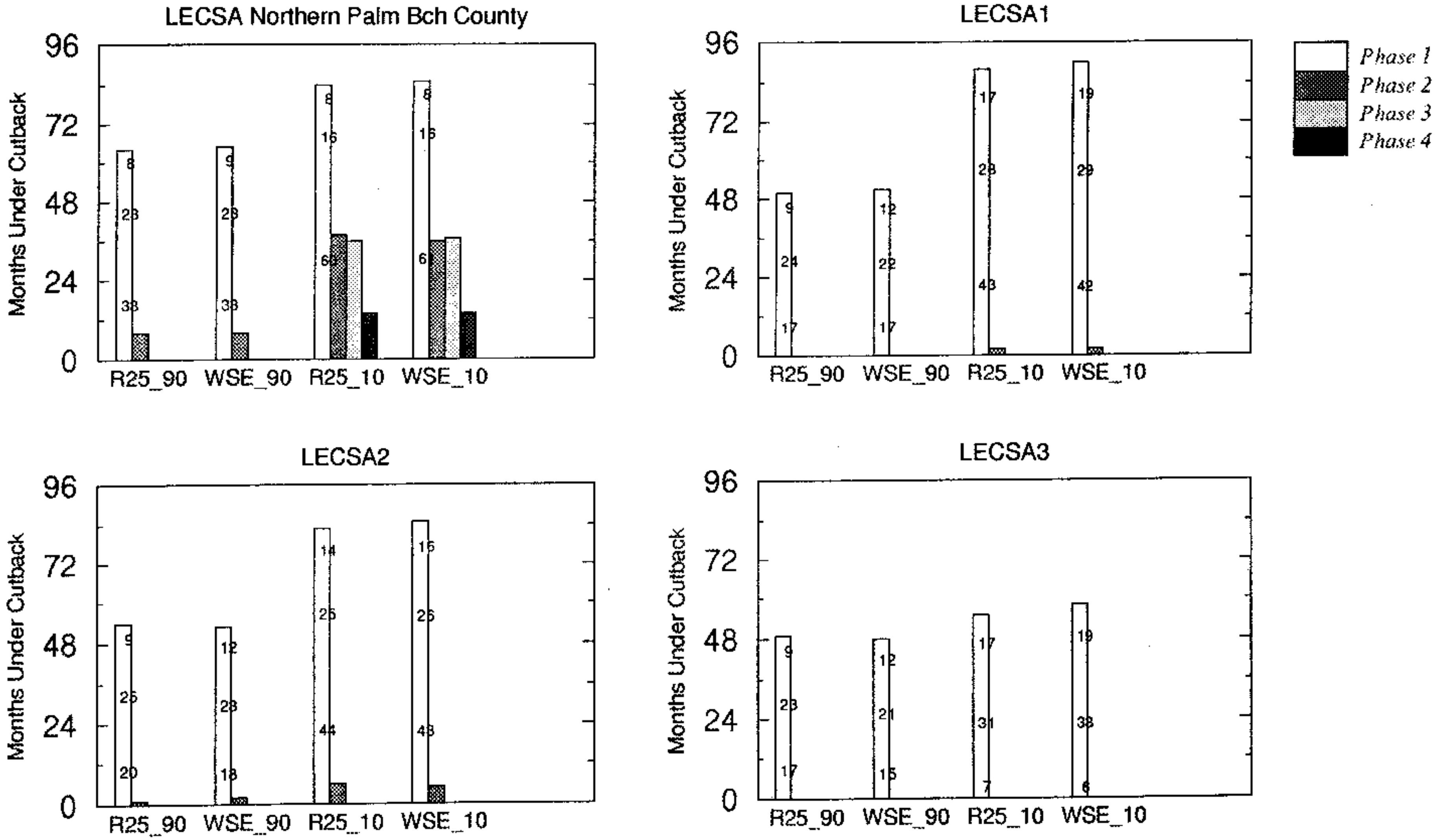
E-59

Note: Structure flows included: SA1=S39+LWDD+ADDSLW+ACMEWS+WSL8S+HLFASR+C51FAS+WSC1+S1ATHL+CPBRWS
SA2=S38+S34+NNRFAS; SA3=S31+S334+S337+BRDRWS+LBTC6+LBTDBL+LBTL30+LBTSC+LBTC9+LBTC2+C9RWS
Supply RECEIVED from LOK may be less than what is DELIVERED at LOK due to conveyance constraints.
Regional System is comprised of LOK and WCAs. It does not include WPAs or any other storage areas.

Run date: 04/24/98 11:22:11
For Planning Purposes Only
SFWMM V3.2

Number of Months of Simulated Water Supply Cutbacks

for the 1965 – 1995 Simulation Period



Note: Phase 1 water restrictions could be induced by a) Lake stage in Supply Side Management Zone (indicated by upper data label),
b) Local Trigger well stages (lower data label), and c) Dry season criteria (indicated by middle data label).

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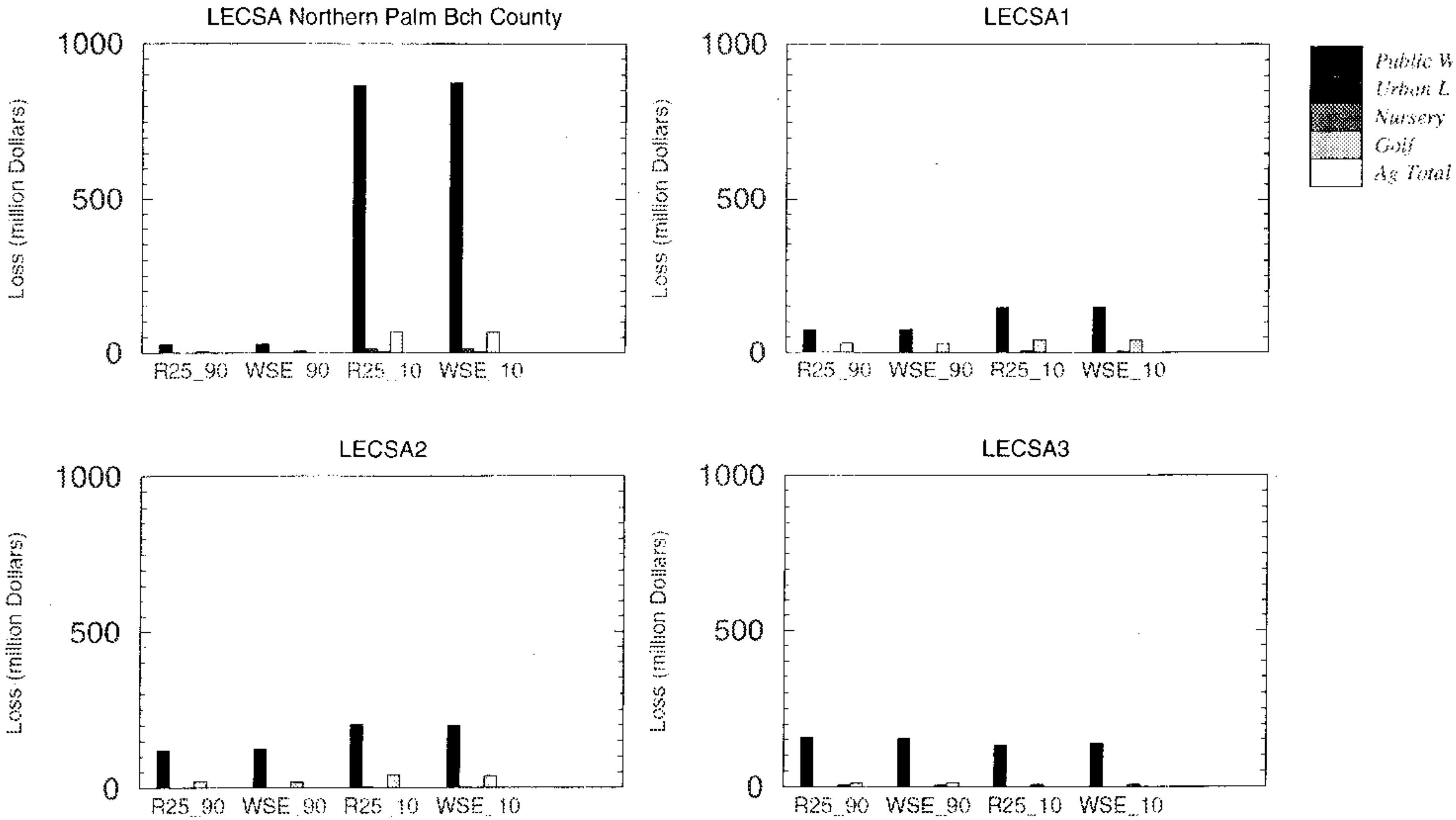
Total Water Shortage Impacts (Losses) for the 31 year Simulation Period



E-61

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For Planning Purposes Only
SFWMM V3.2

APPENDIX F. Environmental Performance Measures - LORSS

I. LAKE OKEECHOBEE LITTORAL ZONE:

Performance Measure No. 1: Similarity in Lake Stages- The lake stage (median depth, 25 and 75 percentile break-points) of each lake regulation schedule alternative will be compared to the period of historical record (1950-1972).[1] Alternatives which have the greatest degree of similarity with the historical record will be considered better.

[1] Outputs to be analyzed include: a whisker box plot type analysis of lake stage

Principal Objective: Protect littoral zone aquatic resources, and improve waterfowl and wading bird habitat.

Rationale: The marsh community that developed during the 1950-1972 time period most closely resembles the "desired" condition for this portion of Lake Okeechobee. The fluctuation in lake stage during this time period is assumed to have led to the development of this community. The alternatives that demonstrate stages that are most similar to this historical record should sustain or rejuvenate these marsh communities.

Citations: Hanlon, C. G., 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Havens, K. E., 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Johnson, C., 1996. Letter from U.S. Fish & Wildlife Service dated April 20, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Rosen, B. H., 1996. South Florida Water Management District. Personal Communication.

Smith, J.P., Richardson, J.R. & Collopy, M.W. (1995): Foraging habitat selection among wading birds at Lake Okeechobee, Florida in relation to hydrology and vegetative cover: a broad overview.- Arch. Hydrobiol. Beih. Ergebn. Limnol. 45: 247-285.

Stage Hydrographs for Lake Okeechobee, Florida: period of record 1950 to 1972. U.S. Army Corps of Engineers, Jacksonville District, Engineering Division.

Performance Measure No. 2: Similarity in Flooding Duration- The duration (median length of time, 25 and 75 percentile break-points) for each lake stage event over 15.0 feet NGVD for each lake regulation schedule alternative, will be compared to the period of historical record (1950-1972).[1] Alternatives which have the greatest degree of similarity with the historical record will be considered better.

[1] Outputs to be analyzed include: a whisker box plot type analysis of lake stage duration above 15.0 feet NGVD

Principal Objective: Improve marsh and littoral zone ecosystem health, diversity and productivity.

Rationale: The marsh zone in Lake Okeechobee developed after the Herbert Hoover Dike system was constructed and is constrained to areas within the dike. During periods of abundant rainfall, the marsh may become completely inundated, which starts when lake stage reaches 15.0 feet NGVD. Occasional inundation is part of the normal cycle for marsh plants. However, if the marsh experiences prolonged high lake stages, certain vegetative communities suffer ecological harm, including willow habitat, and submerged aquatic vegetation. In addition, fish and wildlife associated with these habitats are also harmed. By optimizing the duration that the lake remains above 15.0 feet NGVD, ecological harm caused by prolonged high water may be reduced, and the benefits of occasional high water are sustained.

Citations: David, P. (1994): Wading bird nesting at Lake Okeechobee, Florida: An historic perspective-Colon. Waterbirds 17: 69-77.

Hanlon, C. G., 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Hartman, B. J. (1996). Letter from Florida Game and Fresh Water Fish Commission dated April 23, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Havens, K. E., 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Johnson, C., 1996. Letter from U.S. Fish & Wildlife Service dated April 20, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Minimum Flows and Levels Criteria, draft document dated March 5, 1996. South Florida Water Management District.

Richardson et al. (1995): GIS modeling of hydroperiod, vegetation, and soil nutrient relationships in the Lake Okeechobee marsh ecosystem.-Arch. Hydrobiol. Beih. Ergebn. Limnol. 45: 95-115.

Rosen, B. H., 1996. South Florida Water Management District. Personal Communication.

Smith et al. (1995): Foraging habitat selection among wading birds (Ciconiiformes) at Lake Okeechobee, Florida in relation to hydrology and vegetative cover.-Arch. Hydrobiol. Beihl Ergebn. Limnol. 45: 247-285.

Stage Hydrographs for Lake Okeechobee, Florida: period of record 1950 to 1972. U.S. Army Corps of Engineers, Jacksonville District, Engineering Division.

Performance Measure No. 3: Number, Duration and Frequency of Return of Periodic Lower Lake Stages- The number of lake stage events below 12.0 feet NGVD during the dry season occurring no more and no less than every 3 years, and for no more than 120 days and no less than 90 days, will be compared for each lake regulation schedule alternative.[1] Alternatives which meet this periodic low lake stage will be considered better. The number of lake stage events below 11.0 feet NGVD during the dry season occurring no more and no less than every 7 years, and for no more than 120 days and no less than 90 days, will be compared for each alternative.[2] Alternatives which meet this periodic low lake stage will be considered better. Note: a greater than 7 year return frequency below 11.0 feet NGVD will be ranked worse compared to a greater than 7 year return frequency event.

[1,2] Outputs to be analyzed include: a whisker box plot type analysis of lake stage duration: 1) below 12.0 feet NGVD; 2) below 11.0 feet NGVD; 3) frequency of return below 12.0 feet NGVD for 90-120 days; and 4) frequency of return below 11.0 feet NGVD for 90-120 days.

Principal Objective: Improve wading bird foraging efficacy, nesting success and productivity.

Rationale: Periodic short-term drying of the littoral zone and marsh ecosystem may ensure the health of willow nesting habitat, encourage the development of successional complexes of vegetation that attract a variety of bird life for foraging, encourage nutrient recycling, and allow fires to clear thick and unproductive cattail and torpedo grass.

Citations: Aumen, N.G. and Gray, S. (1995): Research synthesis and management recommendations from a five-year, ecosystem-level study of Lake Okeechobee, Florida (USA).-Arch. Hydrobiol. Beih. Ergebn. Limnol. 45: 343-356.

David, P. (1994): Wading bird nesting at Lake Okeechobee, Florida: An historic perspective-Colon. Waterbirds 17: 69-77.

Hartman, B. J. (1996). Letter from Florida Game and Fresh Water Fish Commission dated April 23, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Havens, K. E., 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Minimum Flows and Levels Criteria, draft document dated March 5, 1996. South Florida Water Management District.

Richardson et al. (1995): GIS modeling of hydroperiod, vegetation, and soil nutrient relationships in the Lake Okeechobee marsh ecosystem.-Arch. Hydrobiol. Beih. Ergebn. Limnol. 45: 95-115.

Rosen, B. H., 1996. South Florida Water Management District. Personal Communication.

Smith et al. (1995): Foraging habitat selection among wading birds (Ciconiiformes) at Lake Okeechobee, Florida in relation to hydrology and vegetative cover.-Arch. Hydrobiol. Beihl Ergebn. Limnol. 45: 247-285.

Stage Hydrographs for Lake Okeechobee, Florida: period of record 1950 to 1972. U.S. Army Corps of Engineers, Jacksonville District, Engineering Division.

Performance Measure No. 4: Moderate Lake Stage Recession- The various lake stage regulation schedule alternatives will be compared to see which alternative demonstrates the greatest degree of similarity to the following lake stage recession scenario: a moderate recession of lake stage to below 14.0 feet NGVD during the period from January to May with no reversal greater than 0.5 feet over a 15 day period.[1] The optimal alternative shall be judged as the one with the maximum number of years which display this pattern.

[1] The outputs to be analyzed include stage hydrographs

Principal Objective: Improve wading bird foraging efficacy, nesting success and productivity.

Rationale: A gradual recession in lake stage, coincident with the wading bird breeding season, has reduced nest flooding, and concentrates prey organisms in submerged aquatic vegetation, canals, and air boat trails within the marsh zone. Moreover, the highest wading bird foraging activities, highest nesting activity among most species, and highest per nest productivity among all wading birds, were associated with gradually declining lake stage.

Citations: Aumen, N.G. and Gray, S. (1995): Research synthesis and management recommendations from a five-year, ecosystem-level study of Lake Okeechobee, Florida (USA).-Arch. Hydrobiol. Beih. Ergebn. Limnol. 45: 343-356.

David, P. (1994): Wading bird nesting at Lake Okeechobee, Florida: An historic perspective-Colon. Waterbirds 17: 69-77.

Havens, K. E., 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Smith et al. (1995): Foraging habitat selection among wading birds (Ciconiiformes) at Lake Okeechobee, Florida in relation to hydrology and vegetative cover.-Arch. Hydrobiol. Beihl Ergebn. Limnol. 45: 247-285.

II. WATER CONSERVATION AREAS:

Performance Measure No. 1: Using output from the SFWMM, for each lake regulation schedule alternative, compare water depths, inundation frequencies, seasonal timing, frequency that each area dries out, and the average length of time between drawdowns at key water management gages located throughout the WCAs, including: for WCA-1: gage 1-7; for WCA-2A: gage 2-17; for WCA-3A: gages 3A-2 (62), 3A-3 (63), 3A-4 (64) and 3A-28 (65); for WCA-2B: Site 99; and for WCA-3B: gages 76, 71, 34, and SRS-1 . Alternatives which best approach natural system hydroperiods (as defined by the Natural Systems Model, or if available, a re-scaled NSM), will be considered better.

Principal Objective: Provide more natural hydrologic conditions within the WCAs and protect and enhance environmental factors and habitat for native fish and wildlife species.

Rationale: Recapturing the hydrologic characteristics (hydropatterns) of the natural system (as estimated by NSM) will maximize recovery of the remaining Everglades Landscape Patterns...which will in turn, provide favorable habitat conditions for the recovery of Everglades wildlife populations.

Citations: Beissinger, Steven R. (1995): Modeling Extinction in Periodic Environments: Everglades Water Levels and Snail Kite Population Viability. Ecological Applications, 5(3), pp. 618-631.

Lower East Coast Regional Water Supply Plan; Revised Draft Preview Document. SFWMD, dated February 1995.

Performance Measure No. 2: Using stage hydrograph and stage duration outputs from the SFWMM, compare water elevations and inundation frequencies of tree island dominated wetlands within all WCAs. Outputs will be analyzed to determine which lake regulation schedules cause the least exceedance of water elevation 10.4 feet NGVD[1] in south WCA-3A, and 12.5 feet NGVD[2] in north WCA-3A, in both number of days and frequency of event over a 25 year simulation period.

[1] As measured by a 2 gage average of gage 64 and gage 65
[2] As measured by a 2 gage average of gage 62 and gage 63

Principal Objective: Protect native everglades vegetation (tree islands) and wildlife communities.

Rationale: Various regulation schedules for Lake Okeechobee have regularly caused high water conditions in the WCAs. During high water events, this has caused flooding of tree island communities and impacts to native everglades vegetation and wildlife.

Citations: Caughlin, S. 1996. Florida Game & Fresh Water Fish Commission. Pers Comm.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Performance Measure No. 3: Using stage hydrograph and stage duration outputs from the SFWMM, compare low water elevations within all WCAs. Outputs will be analyzed to determine the number of times that water elevations fall greater than 1.0 feet below the ground surface for greater than 30 days. Those lake regulation schedules which demonstrate the least exceedance of said event will be judged as better.

Principal Objective: Reduce the probability of Everglades muck fires in peat soils, and protect native everglades vegetation (tree islands) and wildlife communities.

Rationale: Various regulation schedules for Lake Okeechobee have caused seasonal drying out of certain areas within the WCAs. When Everglades vegetation and soils become very dry over a period of time, the probability of fire is greatly increased. Hot, muck fires particularly can cause extreme soil degradation, subsidence, long term harm to fish and wildlife resources and the environment.

By maintaining soil inundation during periods of increased probability of fire, the occurrence of muck fires is decreased and fish and wildlife habitat is protected.

Citations: Minimum Flows and Levels Criteria, draft document dated March 5, 1996. South Florida Water Management District.

Schuette, J. R. (1996). Florida Game and Fresh Water Fish Commission. Pers. Comm.

III. ST. LUCIE AND CALOOSAHATCHEE RIVER ESTUARIES:

Performance Measure No. 1a: St. Lucie Estuary: for each lake regulation schedule alternative, compare the number of times that minimum mean monthly flows from the lake and watershed fall below 350 cfs at S-80 for the entire 1965-1990 period of record.[1] The regulation schedule alternative with the least number of times flows fall below 350 cfs, as measured at S-80, will be considered better for protecting aquatic vegetation, seagrasses, invertebrates, and fish communities. The target is to have no more than 48 violations for the entire 1965-1990 period of record.

[1] Output will be presented as a bar graph with alternatives on x axis and # times minimum mean monthly flow criteria not met (violations) on y axis

Performance Measure No. 1b: St. Lucie Estuary: for each lake regulation schedule alternative, compare the number of times the minimum discharge criteria (average flows less than 350 cfs at S-80) were not met for 1, 2, 3...consecutive months for the entire 1965-1990 period of record.[2] The regulation schedule alternative with the least number of consecutive violations of this criteria will be considered better for protecting aquatic vegetation, seagrasses, invertebrates, and fish communities.

[2] Output will be presented as a bar graph with alternatives on x axis and # consecutive months (violations) on y axis

Principal Objective: Maintain sufficient minimum mean monthly flows from the lake to augment basin runoff, when necessary, in order to maintain favorable salinity envelopes and water quality within the estuary.

Rationale: Insufficient fresh water discharges during the dry season, contribute to poor estuarine water quality including inadequate fresh water to maintain desirable salinity envelopes. These events have had direct effects on estuarine seagrasses, fish and invertebrates, including critical indicator species eg. the American oyster and Vallisneria, by enabling the estuary to become too saline. Note: this performance measure is a preliminary Pollutant Load Reduction Goal (PLRG) being evaluated by the SFWMD through the Indian River Lagoon Surface Water Improvement and Management (SWIM) Program as required by State Water Policy.

Citations: Chamberlain, R., and D. Hayward, 1996. Evaluation of water quality and monitoring in the St. Lucie Estuary, Florida. Water Resources Bulletin. 32(4) 681-696.

Espey, Jr. W.H. and P.G. Cobbs (eds). Proceedings First International Conference, Water Resources Engineering, American Society of Civil Engineers (ASCE). 1506-1510.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Haunert, D.E., 1986. Proposed supplemental water management strategy to enhance fisheries in the St. Lucie Estuary, FL (Draft). SFWMD.

Haunert, D.E. and J.R. Startzman, 1980. Some seasonal fisheries trends and effects of a 1,000 cfs freshwater discharge on the fisheries and macroinvertebrates in the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 80-3.

Haunert, D.E. and J.R. Startzman, 1985. Short term effects of a freshwater discharge on biota of the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 85-1.

Indian River Lagoon SWIM Plan, 1996.

Morris, F.W. 1987. Modeling of hydrodynamics and salinity in the St. Lucie Estuary. South Florida Water Management District: Technical Publication 87-1.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Otero, J.M., J.W. Labadie, D.E. Haunert and M.S. Daron, 1995. Optimization of managed runoff to the St. Lucie Estuary. Water Resources Engineering, Vol. 2.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No. 2a: St. Lucie Estuary: for each lake regulation schedule alternative, compare the number of times the 14 day moving average exceeded 1,600 cfs as measured at S-80 from the lake and the watershed for the entire 1965-1990 period of record. [1] The regulation schedule alternative with the least number of times this criteria is exceeded, at any time of the year, will be considered better for protecting water quality within the estuary. The allowable violations (target) for natural variation is 4, for the entire 1965-1990 test period of record.

[1] Output will be presented as a bar graph with alternatives on x axis and # times 14 day moving average exceeded 1,600 cfs (violations) on y axis

Performance Measure No. 2b: St. Lucie Estuary: for each lake regulation schedule alternative, compare the additional number of times the 14 day moving average flow to the estuary exceeds the 1,600 cfs criteria for 14 days due to discharges from the lake for the entire 1965-1990 period of record.[2]

[2] Output will be presented as a bar graph with alternatives on x axis and additional # times criteria exceeded (violations) on y axis

Performance Measure No. 2c: St. Lucie Estuary: for each lake regulation schedule alternative, compare the number of times the maximum discharge criteria (average flows greater than 1,600 cfs for greater than 14 days from the watershed and the lake) were exceeded for 1, 2, 3...consecutive months for the entire 1965-1990 period of record.[3] The regulation schedule with the shortest duration of violations of the criteria will be considered better for protecting aquatic vegetation, seagrasses, invertebrates, and fish communities.

[3] Output will be presented as a bar graph with alternatives on x axis and # of consecutive months (violations) on y axis

Principal Objective: Achieve and overall reduction in high volume discharge events to the estuary, and improve estuarine water quality with a view to protecting estuarine vegetation, invertebrates, and fish communities.

Rationale: High volume discharges to the estuary contribute to poor estuarine water quality including increased turbidity, color and exceedance of favorable salinity envelopes. These events have had direct effects on estuarine seagrasses by reducing light penetration necessary for photosynthesis, destroying fish and invertebrate habitat, and contributing to unfavorable salinity concentrations for aquatic vegetation, fish and invertebrates, including critical indicator species eg. the American oyster and shoal grass. Note: this performance measure is a preliminary Pollutant Load Reduction Goal (PLRG) being evaluated by the SFWMD through the Indian River Lagoon Surface Water Improvement and Management (SWIM) Program as required by State Water Policy.

Citations: Chamberlain, R., and D. Hayward, 1996. Evaluation of water quality and monitoring in the St. Lucie Estuary, Florida. Water Resources Bulletin. 32(4) 681-696.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Haunert, D.E., 1986. Proposed supplemental water management strategy to enhance fisheries in the St. Lucie Estuary, FL (Draft). SFWMD.

Haunert, D.E. and J.R. Startzman, 1980. Some seasonal fisheries trends and effects of a 1,000 cfs freshwater discharge on the fisheries and macroinvertebrates in the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 80-3.

Haunert, D.E. and J.R. Startzman, 1985. Short term effects of a freshwater discharge on biota of the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 85-1.

Indian River Lagoon SWIM Plan, 1996.

Morris, F.W. 1987. Modeling of hydrodynamics and salinity in the St. Lucie Estuary. South Florida Water Management District: Technical Publication 87-1.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Otero, J.M., J.W. Labadie, D.E. Haunert and M.S. Daron, 1995. Optimization of managed runoff to the St. Lucie Estuary. Water Resources Engineering, Vol. 2.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No 3a: St. Lucie Estuary: for each lake regulation schedule alternative, compare the number of times mean monthly flows from the lake and watershed exceeds 2,500 cfs at S-80 for the entire 1965-1990 period of record.[1] The regulation schedule alternative with the least number of months that flows exceed 2,500 cfs will be considered better for protecting the integrity of the inner and outer estuary. The allowable target violations for natural variation is 4 months for the entire 1965-1990 period of record.

[1] Output will be presènted as a bar graph with alternatives on x axis and # times mean monthly flows exceeded 2,500 cfs (violations) on y axis

Performance Measure No 3b: St. Lucie Estuary: for each lake regulation schedule alternative, compare the number of times mean monthly flows from the lake and watershed exceeded 2,500 cfs for 1, 2, 3...consecutive months for the entire 1965-1990 period of record.[2] The regulation schedule with the least number of consecutive violations of this criteria will be considered better for protecting aquatic vegetation, seagrasses, invertebrates, and fish communities.

[2] Output will be presented as a bar graph with alternatives on x axis and # consecutive months (violations) on y axis

Principal Objective: Reduce the occurrence of extreme discharge events and improve water quality in the inner and outer estuary to protect estuarine vegetation, invertebrates, and fish communities.

Rationale: Mean monthly flows above 2,500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota. This volume of flows, also begin to impact the Indian River Lagoon to the north and south of the St. Lucie Estuary inlet.

Citations: Chamberlain, R., and D. Hayward, 1996. Evaluation of water quality and monitoring in the St. Lucie Estuary, Florida. Water Resources Bulletin. 32(4) 681-696.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Haunert, D.E., 1986. Proposed supplemental water management strategy to enhance fisheries in the St. Lucie Estuary, FL (Draft). SFWMD.

Haunert, D.E. and J.R. Startzman, 1980. Some seasonal fisheries trends and effects of a 1,000 cfs freshwater discharge on the fisheries and macroinvertebrates in the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 80-3.

Haunert, D.E. and J.R. Startzman, 1985. Short term effects of a freshwater discharge on biota of the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 85-1.

Indian River Lagoon SWIM Plan, 1996.

Morris, F.W. 1987. Modeling of hydrodynamics and salinity in the St. Lucie Estuary. South Florida Water Management District: Technical Publication 87-1.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Otero, J.M., J.W. Labadie, D.E. Haunert and M.S. Daron, 1995. Optimization of managed runoff to the St. Lucie Estuary. Water Resources Engineering, Vol. 2.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No. 4a: St. Lucie Estuary: Determine the number of days of Zone A discharge from the lake, (7,200 cfs per day for the St. Lucie at S-80) for each lake regulation schedule alternative for the entire 1965-1990 period of record.[1] Those schedules with the least number of days of Zone A release, according to output from the SFWMM, will be considered better for protecting the integrity of the estuarine environment.

[1] Output will be presented as a bar graph with alternatives on x axis and # days of Zone A discharge (violations) on y axis

Performance Measure No. 4b: St. Lucie Estuary: Determine the number of times Zone A discharge occurs for 1, 2, 3...consecutive days for the entire 1965-1990 period of record.[2] The regulation schedule with the least number of consecutive days of Zone A discharge to the St. Lucie Estuary will be considered better for protecting estuarine aquatic life in the St. Lucie Estuary, Indian River Lagoon, and adjacent waters of the Atlantic Ocean.

[2] Output will be presented as a bar graph with alternatives on x axis and # consecutive days on y axis

Principal Objective: Reduce the occurrence of extreme discharge events from the lake to the estuary, and improve estuarine water quality with a view to protecting estuarine vegetation, invertebrates, and fish communities.

Rationale: Zone A discharges transport large amounts of sediment and rapidly turns the entire inner estuarine ecosystem to freshwater. These events have rapid and serious effects on estuarine seagrasses by reducing light penetration necessary for photosynthesis, destroying fish and invertebrate habitat, and contributing to unfavorable salinity concentrations for most aquatic life, including critical indicator species eg. the American oyster, and a number of sea grass species. These large volume discharges also cause adverse effects on large areas of the Indian River Lagoon surrounding the St. Lucie Estuary Inlet and possibly influence nearshore ocean habitats adjacent to the Inlet. The longer Zone A discharges persist, the greater the damage to the various ecosystems, and the farther the effects extend.

Citations: Chamberlain, R., and D. Hayward, 1996. Evaluation of water quality and monitoring in the St. Lucie Estuary, Florida. Water Resources Bulletin. 32(4) 681-696.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Haunert, D.E., 1986. Proposed supplemental water management strategy to enhance fisheries in the St. Lucie Estuary, FL (Draft). SFWMD.

Haunert, D.E. and J.R. Startzman, 1980. Some seasonal fisheries trends and effects of a 1,000 cfs freshwater discharge on the fisheries and macroinvertebrates in the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 80-3.

Haunert, D.E. and J.R. Startzman, 1985. Short term effects of a freshwater discharge on biota of the St. Lucie Estuary, Florida. SFWMD Tech. Pub. 85-1.

Indian River Lagoon SWIM Plan, 1996.

Morris, F.W. 1987. Modeling of hydrodynamics and salinity in the St. Lucie Estuary. South Florida Water Management District: Technical Publication 87-1.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Otero, J.M., J.W. Labadie, D.E. Haunert and M.S. Daron, 1995. Optimization of managed runoff to the St. Lucie Estuary. Water Resources Engineering, Vol. 2.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No. 5a: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the number of times that minimum mean monthly flows from the lake and watershed falls below 300 cfs at S-79 for the entire 1965-1990 period of record.[1] The regulation schedule alternative with the least number of times flows fall below 300 cfs, as measured at S-79, will be considered better for protecting estuarine aquatic biota. The allowable violations (target) for natural system variation is 54 for the entire 1965-1990 test period of record.

[1] Output will be presented as a bar graph with alternatives on x axis and # months flow criteria not met (violations) on y axis

Performance Measure No. 5b: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the number of times the minimum mean monthly flow of 300 cfs were not met for 1, 2, 3...consecutive months for the entire 1965-1990 period of record.[2] The regulation schedule alternative with the least number of consecutive months with flows below 300 cfs, will be considered better for protecting estuarine aquatic biota.

[2] Output will be presented as a bar graph with alternatives on x axis and # consecutive months on y axis

Principal Objective: Maintain sufficient minimum mean monthly flows from the lake to augment basin runoff, when necessary, in order to maintain favorable salinity envelopes and water quality within the estuary.

Rationale: Insufficient fresh water discharges, contribute to poor estuarine water quality including inadequate fresh water to maintain desirable salinity envelopes. These events have had direct effects on estuarine seagrasses, fish and invertebrates, including critical indicator species eg. Vallisneria, by enabling the estuary to become too saline. Note: this performance measure is a preliminary Pollutant Load Reduction Goal (PLRG) being evaluated by the SFWMD.

Citations: Bierman, V. 1993. Performance report for the Caloosahatchee Estuary salinity modeling. SFWMD Expert Assistance Contract, deliverable from Limno Teck, Inc.

Chamberlain, R., D. Haunert, P. Doering, K. Haunert, and J. Otero. 1995. Preliminary estimate of optimum freshwater inflow to the Caloosahatchee Estuary, Florida.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No 6a: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the number of times mean monthly discharge from the lake and watershed exceeds 2,800 cfs at S-79 for the entire 1965-1990 period of record.[1] The regulation schedule alternative with the least number of times flows exceed 2,800 cfs as measured at S-79, at any time of year, will be considered better for maintaining water quality within the estuary. The allowable violations (target) for natural variation is 17 for the entire 1965-1990 period of record.

[1] Output will be presented as a bar graph with alternatives on x axis and # times mean monthly discharge exceeded 2,800 cfs (violations) on y axis

Performance Measure No 6b: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the additional number of months that flow to the estuary, exceeds 2,800 cfs at S-79, due to regulatory releases from the lake, for the entire 1965-1990 period of record.[2] The regulation schedule alternative with the least number of additional months that flows exceed 2,800 cfs will be considered better for maintaining water quality within the estuary.

[2] Output will be presented as a bar graph with alternatives on x axis and # additional months flow criteria exceeded (violations) on y axis

Performance Measure No 6c: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the number of times the high discharge criteria (mean flow is greater than 2,800 cfs) from the watershed and lake were exceeded at S-79 for 1, 2, 3...consecutive months for the entire 1965-1990 period of record.[3] The regulation schedule with the shortest duration of violations of this criteria will be considered better for protecting estuarine aquatic biota.

[3] Output will be presented as a bar graph with alternatives on x axis and # consecutive months (violations) on y axis

Principal Objective: Achieve an overall reduction in high volume discharge events to the estuary, and improve estuarine water quality with a view to protecting estuarine vegetation, invertebrates, and fish communities.

Rationale: High volume discharges to the estuary contribute to poor estuarine water quality including increased turbidity, color and exceedance of favorable salinity envelopes. These events have had direct effects on estuarine seagrasses by reducing light penetration necessary for photosynthesis, destroying fish and invertebrate habitat, and contributing to unfavorable salinity concentrations for aquatic vegetation, fish and invertebrates, including critical indicator species eg. the American oyster, turtle grass, and Vallisneria. Note: this performance measure is a preliminary Pollutant Load Reduction Goal (PLRG) being evaluated by the SFWMD.

Citations: Bierman, V. 1993. Performance report for the Caloosahatchee Estuary salinity modeling. SFWMD Expert Assistance Contract, deliverable from Limno Teck, Inc.

Chamberlain, R., D. Haunert, P. Doering, K. Haunert, and J. Otero. 1995. Preliminary estimate of optimum freshwater inflow to the Caloosahatchee Estuary, Florida.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No 7a: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the number of times mean monthly flows from the lake and watershed exceed 4,500 cfs at S-79 for the entire 1965-1990 period of record.[1] The regulation schedule alternative with the least number of months that discharges exceed 4,500 cfs as measured at S-79, will be considered better for protecting estuarine resources, including those downstream in the San Carlos Bay region. The allowable target violations for natural system variation is 5 months in the entire test period of record (1965-1990).

[1] Output will be presented as a bar graph with alternatives on x axis and # times mean monthly flow exceeded 4,500 cfs (violations) on y axis

Performance Measure No 7b: Caloosahatchee River Estuary: for each lake regulation schedule alternative, compare the number of times mean monthly flows from the lake and watershed exceeded 4,500 cfs for 1, 2, 3...consecutive months at S-79 for the entire 1965-1990 period of record.[2] The regulation schedule alternative with the least number of consecutive violations for this criteria will be considered better for protecting estuarine aquatic biota.

[2] Output will be presented as a bar graph with alternatives on x axis and # consecutive months flows exceeded criteria (violations) on y axis

Principal Objective: Reduce the occurrence of extreme discharge events and improve water quality in the lower estuary, including San Carlos Bay, in order to protect estuarine resources.

Rationale: Mean monthly flows above 4,500 cfs results in freshwater conditions throughout the entire estuary causing impacts to estuarine biota. This volume of flow also begins to reduce water quality and adversely impact biota in San Carlos Bay.

Citations: Bierman, V. 1993. Performance report for the Caloosahatchee Estuary salinity modeling. SFWMD Expert Assistance Contract, deliverable from Limno Teck, Inc.

Chamberlain, R., D. Haunert, P. Doering, K. Haunert, and J. Otero. 1995. Preliminary estimate of optimum freshwater inflow to the Caloosahatchee Estuary, Florida.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

Performance Measure No 8a: Caloosahatchee River Estuary: determine the number of days of Zone A discharge from the lake (7,800 cfs per day at S-79, not S-77) for each lake regulation schedule alternative for the entire 1965-1990 period of record.[1] Those schedules with the least number of days of Zone A release according to output from the SFWMM will be considered better for protecting the integrity of the estuarine environment.

[1] Output will be presented as a bar graph with alternatives on x axis and # days of Zone A discharge (violations) on y axis

Performance Measure No 8b: Caloosahatchee River Estuary: determine the number of times Zone A discharge occurs for 1, 2, 3... consecutive days for the entire 1965-1990 period of record.[2] The regulation schedule with the least number of consecutive days of Zone A discharge to the

Caloosahatchee River Estuary will be considered better for protecting estuarine aquatic life in the estuary and San Carlos Bay.

[2] Output will be presented as a bar graph with alternatives on x axis and # consecutive days of Zone A discharge (violations) on y axis

Principal Objective: Reduce the occurrence of extreme discharge events from the lake to the estuary, and improve estuarine water quality with a view to protecting estuarine aquatic biota.

Rationale: Zone A discharges have rapid and serious effects on estuarine seagrasses in the Caloosahatchee River Estuary and San Carlos Bay by reducing light penetration necessary for photosynthesis. Zone A discharges destroy fish and invertebrate habitat, and contribute to unfavorable salinity concentrations for many estuarine biota, including critical indicator species eg. the American oyster, Vallisneria, and seagrasses. The longer Zone A discharges persist, the greater the damage to the various ecosystems, and the farther the damage extends.

Citations: Bierman, V. 1993. Performance report for the Caloosahatchee Estuary salinity modeling. SFWMD Expert Assistance Contract, deliverable from Limno Teck, Inc.

Chamberlain, R., D. Haunert, P. Doering, K. Haunert, and J. Otero. 1995. Preliminary estimate of optimum freshwater inflow to the Caloosahatchee Estuary, Florida.

Haunert, D., and R. Chamberlain. 1994. St. Lucie and Caloosahatchee Estuary Performance Measures for Alternative Lake Okeechobee Regulation Schedules. SFWMD Memorandum.

Otero, J. M., and Floris, V. (1994). Lake Okeechobee Regulation Schedule Simulation: South Florida Regional Routing Model. SFWMD. Special Report prepared for the U.S. Army Corps of Engineers, Jacksonville, Florida.

Steinman, A. 1996. Letter from SFWMD dated April 2, 1996 to U.S. Army Corps of Engineers, Jacksonville District.

IV. EVERGLADES NATIONAL PARK AND FLORIDA BAY:

Performance Measure No. 1: Using output from the SFWMM, for each lake regulation schedule alternative, compare water depths, inundation frequencies, seasonal timing, frequency that each area dries out, and the average length of time between water level recessions, at key water management gages located throughout ENP including: (gages) P33, G620, NP201, NE1, NE2, TSB, EPSW/GW, NP205, and CP. Alternatives which best approach the spatial and temporal patterns of the NSM will be considered better.

Principal Objective: Protect Shark Slough and Taylor Slough flora and fauna including adjacent short hydroperiod wetlands and estuaries.

Rationale: Drainage of the original Everglades has affected the volume, timing, and distribution of water flow. The historical storage within the wetlands has been greatly reduced. By maximizing the available storage in the system, future restoration efforts may become possible.

Citations: Johnson, R.A. and VanLent, T.S. 1994. Restoring flows to the Shark Slough Basin, Everglades National Park.

Johnson, R.A. Preliminary Recommendations for Improved Water Management and Increased Water Deliveries to ENP.

SFNRC at Everglades National Park, 1994. Restoration of Northeastern Shark Slough and the Rocky Glades.

U.S. Army Corps of Engineers, Jacksonville District, Florida. 1995. Environmental Assessment and Finding of No Significant Impact. Test Iteration 7, Experimental Program of Water Deliveries to Everglades National Park.

Performance Measure No. 2: For each lake regulation schedule alternative, measure the frequency that flows through the S-12 structures exceed 3,000 cfs/day for more than one week. Those alternatives which reduce the frequency of high volume discharges to downstream wetlands will be considered better for protecting ENP wetland communities.

Principal Objective: Reduce the excessive flood control discharges onto the western peripheral wetlands of Shark Slough.

Rationale: High volume regulatory flows over a prolonged period through the S-12 structures have caused damage to the flora and fauna south of the structures. Restoring more natural flows, both in terms of volume and timing will protect native ecological communities, previously harmed by these flood control discharges.

Citations: Pimm, Stuart L., Annual Report 1996 - Population Ecology of the Cape Sable Sparrow.

Performance Measure No. 3: For each lake regulation schedule alternative, measure the frequency that flows through the S-12 structures exceed regulatory releases. Those alternatives which reduce the frequency of regulatory release exceedance will be considered better for protecting ENP wetland communities.

Principal Objective: To establish a functioning rainfall plan for Shark Slough.

Rationale: High volume regulatory flows over a prolonged period through the S-12 structures have caused damage to the flora and fauna south of the structures. Restoring more natural flows, both in terms of volume and timing will protect native ecological communities, previously harmed by these flood control discharges.

Citations: Neidrauer, C.J., and R.M. Cooper, November 1989. A two year field test of the rainfall plan for water deliveries to Everglades National Park. South Florida Water Management District, Tech. Pub. 89-3.

APPENDIX G. Correspondence

South Florida Water Management District
3301 Gun Club Road, West Palm Beach, Florida 33406 • (561) 686-8800 • FL WATS 1-800-432-2045
TDD (561) 697-2574

PRO LO SWIM

April 30, 1997

Richard E. Bonner, Deputy
District Engineer for Project Management
Department of the Army
Jacksonville District Corps of Engineers
P.O. Box 4970
Jacksonville, FL 32232-0019

Dear Mr. Bonner:

Re: Modeling Results for the Lake Okeechobee Regulation Schedule Study

As requested in your letter dated March 12, 1997, the South Florida Water Management District (SFWMD) is providing the modeling output and preliminary evaluation of the alternatives for the Lake Okeechobee Regulation Schedule Study. The report enclosed should be considered DRAFT, as it is undergoing internal review. We also anticipate input from your staff prior to finalizing this report to ensure it meets your needs for the Environmental Impact Statement.

As you requested, this report, along with post-processor output, will be provided to Mr. Ken Murray of the Natural Resources Conservation Service.

If you have any questions, please feel free to contact me at 561/687-6348; questions about the modeling should be directed to Cal Neidrauer at 561/687-6506.

Sincerely,

Barry H Rosen

Barry H. Rosen, Senior Environmental Scientist
Upper East Coast/Kissimmee Division

BR:ce
Enclosure

Mailing Address: P.O. Box 24680, West Palm Beach, FL 33416-4680

c. Dan Cary, PLN
Dean Powell, PLN
Terry Clark, UEC/K
Susan Gray, UEC/K
Jayantha Obeysekera, HSM
Cal Neidrauer, HSM
Al Steinman, OSR

DEPARTMENT OF THE ARMY
JACKSONVILLE DISTRICT CORPS OF ENGINEERS
P. O. BOX 4970
JACKSONVILLE, FLORIDA 32232-0019

March 12, 1997

REPLY TO
ATTENTION OF

Programs and Project Management Division
Project Management Branch

Mr. Barry Rosen
South Florida Water Management District
Post Office Box 24680
West Palm Beach, Florida 33416-4680

Dear Mr. Rosen:

The purpose of this letter is to provide the final alternatives to be modeled by South Florida Water Management District (SFWMD) for the Lake Okeechobee Regulation Schedule Study. The four alternatives include Run 25, Run 22AZE, an alternative developed by the U.S. Army Corps of Engineers (USACE), and an alternative proposed by the Lower East Coast Regional Water Supply Plan. The regulation schedules for these alternatives are shown as Enclosures 1-4 of this correspondence. See Figures 1-4

It is requested that the four alternatives be modeled using the following demand scenarios: 1990 (base condition), 2010 (developed by SFWMD), and the 2010 with and without conservation (developed by USACE). These 16 model runs including the corresponding performance measures should be completed by April 30, 1997, in order to ensure timely completion of the Draft Environmental Impact Statement. Additionally, it is requested that the output from the South Florida Water Management Model and its economic post-processor be provided to Mr. Ken Murray, of the Natural Resources Conservation Service (NRCS), after completion of each alternative. This delivery method would allow NRCS to be continuously provided data for use in developing crop budgets for the study area.

Your continued support of the Lake Okeechobee Regulation Schedule Study is appreciated. Should you have any questions or comments regarding this request, feel free to contact me or Ms. Kimberly Brooks-Hall at 904-232-3155.

Sincerely,

Richard E. Bonner

Richard E. Bonner, P.E.
Deputy, District Engineer
for Project Management

South Florida Water Management District

3301 Gun Club Road, West Palm Beach, Florida 33406 • (561) 686-8800 • FL WATS 1-800-432-2045

PRO SWIM LO RF: 97002

October 22, 1996

Colonel Terry Rice, District Engineer
U.S. Army Corps of Engineers, Jacksonville District
P.O. Box 4970
Jacksonville, FL 32232-0019

Dear ~~Colonel Rice~~: Terry

In response to your letter of September 25, 1996, verifying the SFWMD ongoing support for the Lake Okeechobee Regulation Schedule Study (LORSS), District staff have been in contact with the Natural Resources Conservation Service (NRCS), and are providing them with the data they need for the evaluation of the economic impacts of the alternative regulation schedules. Two simulations have been provided to the NRCS, while the remaining alternatives are being developed by the SFWMD and your staff.

We concur with the modeling scenarios in your letter concerning the 2010 planning period, including the anticipated hydrologic changes from the projects listed. We also concur that the LORSS will not examine schedules that may require structural modifications that will not be completed in the 2010 planning period.

Your letter suggested that five regulation schedules be evaluated. Four of the alternatives, Run 25 and Run 22-AZE, and the two "new" alternatives (one developed by the COE and one during the Lower East Coast Regional Water Supply Plan (LECRWSP) process), were anticipated for this effort. However, we do not agree that the 1978 schedule should be included. The adoption of Run 25 was, in part, to "permanently eliminate any possibility of a forced return to the 1978 schedule that we and all state agencies agree is unacceptable" (correspondence from Richard Bonner to Tilford Creel, dated August 9, 1994). In addition, elimination of the 1978 schedule will reduce the overall modeling and evaluation by approximately 20%, saving time and financial resources. For our own planning and scheduling, we will also need to know your target deadlines for the modeling effort.

We appreciate the tremendous effort that is currently underway for the LORSS, including the development of new performance measures and economic analysis being conducted by your staff. If your staff or NRCS needs additional information regarding the modeling, please contact Cal Neidrauer, Senior Supervising Engineer, Hydrologic Systems Modeling Division at (561) 687-6506.

Sincerely,

Samuel E. Poole III
Executive Director

SEP/kh
c: Cal Neidrauer, SFWMD

Mailing Address: P.O. Box 24680, West Palm Beach, FL 33416-4680

South Florida Water Management District
3301 Gun Club Road, West Palm Beach, Florida 33406 • (561) 686-8800 • FL WATS 1-800-432-2045

RES 17-06

October 11, 1996

Mr. Ken Murray
Natural Resources Project Planning Coordinator
Natural Resources Conservation Service
P. O. Box 141510
Gainesville, FL 32614

Dear Mr. Murray:

Per our telephone conversation of October 10, 1996, I am enclosing the results of the economics post-processor for the following two simulations performed with the South Florida Water Management Model (SFWMMv2.10-100996).

1. 1990 Base: This simulation assumes ~1990 land use, associated water use demands, and ~1990-era infrastructure and operations. This simulation may not be directly applicable to the Lake Okeechobee Regulation Schedule Study (LORSS), since it assumes 1990-era infrastructure; but it is a useful baseline for the "current" system. It also uses the current Lake Okeechobee Regulation Schedule (Run 25).

2. 2010 Base: This simulation assumes 2010 land use and associated demands as estimated by the South Florida Water Management District. It also assumes the following projects are constructed and operational: Kissimmee River Restoration, Everglades Construction Project, Modified Water Deliveries to Everglades National Park, C-111 GRR Project, and the recently adopted regulation schedule for WCA-1. The current regulation schedule for Lake Okeechobee (Run 25) is also used for this simulation. This simulation is directly applicable to the LORSS.

Results of the economics post-processors for these two simulations are enclosed on two diskettes; one for the 1990 base and one for the 2010 base. Each disk contains the DOS-formatted outputs from the economics post-processors for the Everglades Agricultural Area and the Lower East Coast Service Areas.

Please feel free to call me at (561)687-6506 if you have further questions.

Sincerely,

Calvin J. Neidrauer, P. E.
Senior Supervising Engineer
Hydrologic Systems Modeling Division
Planning Department

CJN/nm
Enclosures (2)

DEPARTMENT OF THE ARMY
JACKSONVILLE DISTRICT CORPS OF ENGINEERS
P. O. BOX 4970
JACKSONVILLE, FLORIDA 32232-0019

September 25, 1996

REPLY TO
ATTENTION OF

Planning Division
Plan Formulation Branch

RECEIVED
SEP 27 1996
EXECUTIVE OFFICE

Mr. Samuel E. Poole, III
Executive Director
South Florida Water
Management District
Post Office Box 24680
West Palm Beach, Florida 33416-4680

Dear Mr. Poole:

The following is to verify ongoing interagency team efforts by both the South Florida Water Management District (SFWMD) and my staff for the Lake Okeechobee Regulation Schedule Study. Thank you for providing the Natural Resources Conservation Service with the economic post processor materials as we requested in our April 5, 1996, letter.

As requested in your previous correspondence dated May 20, 1996, our staff has been in contact with Mr. Cal Niedrauer and others at the SFWMD and have worked out the parameters to be used in running the SFWMM. The planning period will extend no greater than the year 2010 since this regulation schedule change is interim until the recommendations of the Central and Southern Florida Restudy effort can be implemented. For hydrologic modeling purposes, it will be assumed that the following projects will have been built by the year 2010: the Kissimmee River Restoration, the C-111 GRR project, Modified Water Deliveries to Everglades National Park, the Everglades Construction Project and the Modified WCA-1 Regulation Schedule.

* this was printed in error/should be ?? de

Five regulation schedules will be evaluated. The first three are known schedules; the 1978 schedule, Run 25 and Run 22-AZE. During the Environmental Performance Measures Workshop recently held at the SFWMD office, it was decided that both agencies would each submit one additional regulation schedule to be studied as a part of this effort. Alternative 5 from the Lower East Coast Regional Water Supply Plan will not be run since it requires structural modifications that will not be in place before the year 2010. The U.S. Army Corps of Engineers (Corps) will have their alternative available by September 30, 1996. Each of these five regulation schedules will be run using the SFWMD's 1990 and 2010 water demands, as well as the Corps 2010 water demands, both with and without active water conservation measures. Since Runs 25 and 22-AZE have already been run with SFWMD 1990 and 2010 demands, it is requested that copies of the economic post-processor output information be provided to us and the NRCS in both electronic and hard copy formats, so that we can initiate their agricultural analysis.

Lastly, the Corps water use demands are being disaggregated and formatted for the SFWMM and will be provided to SFWMD upon completion.

Your continued support of the Lake Okeechobee Regulation Schedule Study is greatly appreciated.

Sincerely,

Richard E. Bonner

Terry L. Rice
Colonel, U.S. Army
District Engineer

Cc: Nelavaver

DEPARTMENT OF THE ARMY
JACKSONVILLE DISTRICT CORPS OF ENGINEERS
P. O. BOX 4970
JACKSONVILLE, FLORIDA 32232-0019

July 15, 1996

REPLY TO
ATTENTION OF

Planning Division
Environmental Branch

TO THE ADDRESSEES ON THE ENCLOSED LIST:

The Jacksonville District, U.S. Army Corps of Engineers (Corps) in collaboration with the South Florida Water Management District (SFWMD), is planning a meeting/workshop to further discuss and develop environmental performance measures in order to measure and evaluate potential environmental effects of various proposed regulation schedule alternatives for Lake Okeechobee, Florida. The one and a half day meeting/workshop will be held in West Palm Beach, at the SFWMD, Building B-1, Auditorium, beginning at 1:00 p.m. August 20, and continuing until about 3:00 p.m. of the following day. A preliminary agenda is included for your information. The draft performance measures are currently being revised in light of agency input and feedback and will be sent to you prior to the meeting for your review.

The objective of the Lake Okeechobee Regulation Schedule Study is to optimize environmental benefits at minimal or no impact to the competing project purposes, primarily flood control and water supply. The study will propose an interim lake regulation schedule using operational changes only, and will be in effect until the C&SF Project Comprehensive Review Study (Restudy) can implement a more comprehensive solution. Expertise on the lake's littoral zone, downstream estuaries, and Everglades ecosystem will be represented at the meeting. It is hoped that this group can come to a consensus on a set of performance measures for the purposes of this study, which may assist in establishing the groundwork for future development of performance measures for the C&SF Restudy.

Additional information, or questions regarding this meeting may be addressed to Mark Ziminske, Planning Division, U.S. Army Corps of Engineers, telephone 904-232-1786 or via e-mail at: *mark.t.ziminske@usace.army.mil*.

Sincerely,

A. J. Salem

A. J. Salem
Chief, Planning Division

Enclosures

APPENDIX B

WATER QUALITY MODELING RESULTS

Phosphorus Issues Associated with the Lake Okeechobee Regulation Schedule

Barry Rosen, Ph.D.

Executive Summary:

Water entering into the WCAs, and its associated phosphorus load, comes from two sources; the lake (through S-5, S-6, S-7 and S-8) and from EAA runoff. Water from the lake ranges from 5-7% of the total volume entering the WCAs, and has 3-5% of the phosphorus load. Therefore, basin runoff accounts for 93-95% of the water volume and 95-97% of the phosphorus load (see Table 2).

The volume of water released southward for regulatory releases under WSE is simulated to be approximately 14,272 acre-ft greater than Run 25. That additional water brings with it a net of 0.7 ton of phosphorus/year, for 4 years until STAs 3/4 are completed. WSE is also predicted to cause more EAA runoff, which brings another 0.3 tons annually. Therefore, in total, the WSE regulation schedule may result in an additional loading to the WCAs that totals 4 metric tons over 4 years.

Using the most realistic phosphorus concentrations scenarios, those closest to measured values, the Everglades Phosphorus Gradient model predicts that WCA1 actually benefits from a 52-acre reduction in cattail spread under the WSE regulation schedule compared to Run 25 during this 4-year period. This is because less water (12.2 kac-ft/yr) is predicted the WSE schedule; therefore, less phosphorus loading to WCA1. There is an increase in cattail spread in WCA 2A of 9 acres, associated with and additional 7.1 kac-ft/yr of water, and an increase of 3 acres in WCA 3A from an additional 21.3 kac-ft/yr of water. Therefore, the outcome for the entire WCA is approximately 40 fewer acres of cattail under the WSE schedule compared to Run 25 after 4 years.

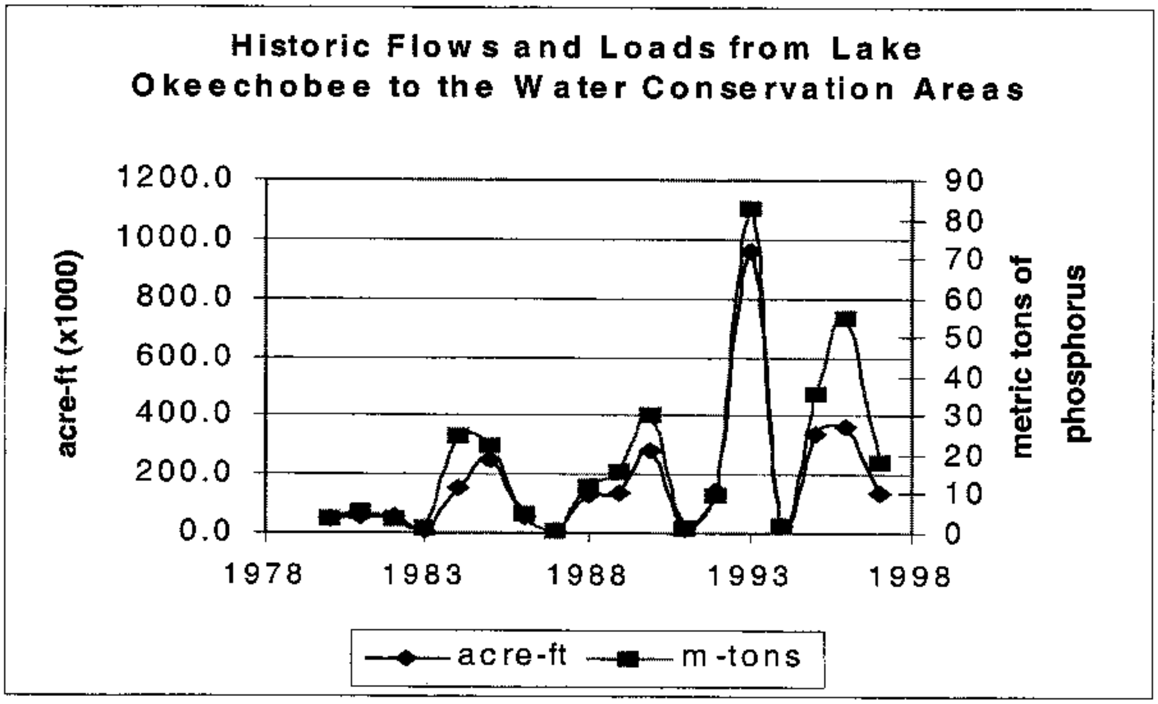
The Everglades Phosphorus Gradient model also predicts the area that becomes greater than 10 ppb in phosphorus concentration. This evaluation is useful for determining the potential impact on periphyton. For WCA1, the area of > 10 ppb is reduced by 1087 acres with the WSE schedule compared to Run 25 in WCA1, increases by 790 acres in WCA 2A and increases by 2,134 acres in WCA 3A relative to Run 25. Therefore, the net increase in area that is predicted to become > 10 ppb is 1,838 acres compared to Run 25 over the 4-year period, out of a total area of approximately 744,960 acres in the WCAs.

Background:

The proposed alternative lake regulation schedule, WSE, increases the amount of water that is released from the lake southward into the Water Conservation Areas (WCAs) compared to the current regulation schedule, Run 25. Concern has been raised that additional water will bring additional phosphorus and potentially impact the WCAs. The US Army Corps of Engineers (USACE) is developing an environmental impact statement for the WSE alternative, and this issue needs to be thoroughly addressed. In general, the phosphorus load is directly proportional to the volume of water, with greater volumes bringing greater loads, as illustrated with measured data on flows and loads into the WCAs (Figure 1).

This report is intended to document the simulated volume of regulatory releases for Run 25 and WSE based on model output so that relative comparisons can be made between these alternatives. This simulated volume then can be used to calculate the expected phosphorus load and potential ecological effects in the WCAs. This information is needed to determine if this additional water would have a significant ecological impact. This modeling effort provides a means of making relative comparisons between alternatives; however, the actual water released is a function of how the canal system is operated (Operations and Maintenance Department, SFWMD). The SFWMD and the USACE are finalizing an Implementation Plan that specifically proscribes the conditions for water release for use by Operations and Maintenance.

Figure 1. Relationship between flows and loads into the WCAs.



Simulated regulatory discharges and historic phosphorus concentrations:

The volume of regulatory releases in acre-ft was simulated for Run 25 and WSE using the South Florida Water Management Model. The modeling effort used the "1995 base", which includes such features as the BMP makeup water, as well as all of the current water management operational practices. This modeling also includes the Implementation Plan developed for WSE (SFWMD 1999 Implementation Report).

This white paper is focused on the regulatory releases that are made southward to the Miami, North New River, Hillsboro, and West Palm Beach canals (Table 1). There is an increase in annual average volume of water released with the WSE schedule; an increase of 14,272 acre-ft is predicted to be released to the canals south of the lake (Table 1).

Table 1. Model output for regulatory discharges south (annual average-acre-ft) and measured flow-weighted mean total phosphorus concentration (1/90-12/97) through the southern canals. (Model output from the South Florida Water Management Model).

	Miami	*North New River*	*Hillsboro*	*West Palm*	**Total**
R25	4,998	9,456	17,561	23,868	55,883
WSE	25,330	16,392	12,203	16,229	70,155
					Δ 14,272
Mean Total P	71.6 ppb	77.2 ppb	77.2 ppb	135.6 ppb	

Stormwater Treatment Areas:

Water quality is an issue of STA performance for the Everglades Forever Act criteria. Therefore, discussion of the impacts in this report will focus on the time period between implementation of the WSE schedule (projected for August, 1999) and the completion of the respective STAs. Briefly, STA1-W and STA-2 will become fully operational in July and August, 2000, respectively. These STAs are not designed to treat regulatory releases from Lake Okeechobee. Implementation of the regulation schedule is anticipated to occur prior to the completion of stormwater treatment areas (STAs) 3/4. Therefore, no water quality treatment is assumed during this interim period. STA 3/4 was initially designed to treat approximately 236,000 acre feet of water from Lake Okeechobee, which exceeds the annual average regulatory discharges south.

Potential WCA impacts:

The South Florida Water Management Model is used initially to describe the amount of water moved through each canal and structure, as well as basin runoff and into the WCAs (Table 2). The distribution of this water affects the anticipated phosphorus load, which is shown in Table 3.

Table 2. Simulated flows to the Water Conservation Areas, with % of total flow calculated for each source.

		Inflow (kac-ft/yr)		% of total	
WCA-1		**Run 25**	**WSE**	**Run 25**	**WSE**
	Lake thru S5	23.9	16.2	5%	3%
	Runoff S5	227.8	228.2	48%	49%
	Lake thru S6	17.6	12.2	4%	3%
	Runoff S6	209.6	210.1	44%	45%
	Total	478.9	466.7		
WCA-2A					
	Lake thru S7	9.5	16.4	4%	7%
	Runoff S7	235.5	235.7	96%	93%
	Total	245	252.1		
WCA-3A					
	Lake thru S8	5	25.3	1%	5%
	Runoff S8	390	390.4	75%	72%
	S150	31.5	32.1	6%	6%
	G155	95.2	95.2	18%	17%
	G204	0.4	0.4	0%	0%
	G205	0.6	0.6	0%	0%
	G206	0.5	0.5	0%	0%
	Total	523.2	544.5		

A second model is needed to determine the effects that the additional phosphorus may have on the WCAs. The second model uses the water volumes and its distribution in the canal system into each WCA to predict potential ecological impacts.

Two phosphorus concentration scenarios were assigned to WCA inflows: 70 and 100 ppb. These scenarios were used to portray the most likely phosphorus concentrations that are currently found in the canals. The simulated volume (from the SFWMM) was combined with these phosphorus scenarios to calculate the potential load and phosphorus concentrations in the WCAs (Table 4). Output from this table was used to determine potential impacts to the WCAs using the Everglades Phosphorus Gradient Model (EPGM), developed by Walker and

Table 3. Simulated loading to the Water Conservation Areas, with % of total load calculated for each source.

		Load P (metric ton/yr)		% of total	
WCA-1	(100 ppb scenario)	**Run 25**	**WSE**	Run 25	WSE
	Lake thru S5	2.9	2.0	4%	2.5%
	Runoff S5	52.2	52.3	65%	66%
	Lake thru S6	2.2	1.5	2.7%	1.9%
	Runoff S6	23.3	23.4	29%	30%
	Total	80.6	79.2		
WCA-2A	(70 ppb scenario)				
	Lake thru S7	0.8	1.4	3%	5%
	Runoff S7	25.4	25.5	97%	95%
	Total	26.3	26.9		
WCA-3A	(70 ppb scenario)				
	Lake thru S8	0.4	2.2	1%	3%
	Runoff S8	52.6	52.7	74%	72%
	S150	2.2	2.2	3%	3%
	G155	15.8	15.8	22%	22%
	G204	0.03	0.03	0.04%	0.04%
	G205	0.04	0.04	0.1%	0.1%
	G206	0.02	0.02	0.02%	0.02%
	Total	71.2	73.0		

Table 4. Simulated regulatory releases south with two WCA inflow scenarios for phosphorus concentration with associated predicted flow-weighted mean total phosphorus concentration (1/90-12/97) and load (metric tons/year) for Run 25 and WSE.

	WCA inflow P conc.	Simulated Lake Out-Flow (kacre-feet/yr)		Predicted Flow-weighted conc. (ppb)		Predicted Load (metric tons/yr)	
	scenarios	Run 25	WSE	Run 25	WSE	Run 25	WSE
WCA 1	70 ppb	41.5	28.4	134.3	136.1	79.1	78.1
Inflow	100 ppb			136.9	137.9	80.6	79.2
WCA 2A	70 ppb	9.5	16.4	87.1	86.6	26.3	26.9
Inflow	100 ppb			88.3	88.6	26.6	27.5
WCA 3A	70 ppb	5	25.3	110.6	109.0	71.2	73
Inflow	100 ppb			110.9	110.4	71.4	74

Kadlec (1996). The model determines steady state phosphorus concentrations in sediments and water, from which it predicts the steady state changes in cattail (coverage) and area that becomes > 10 ppb.

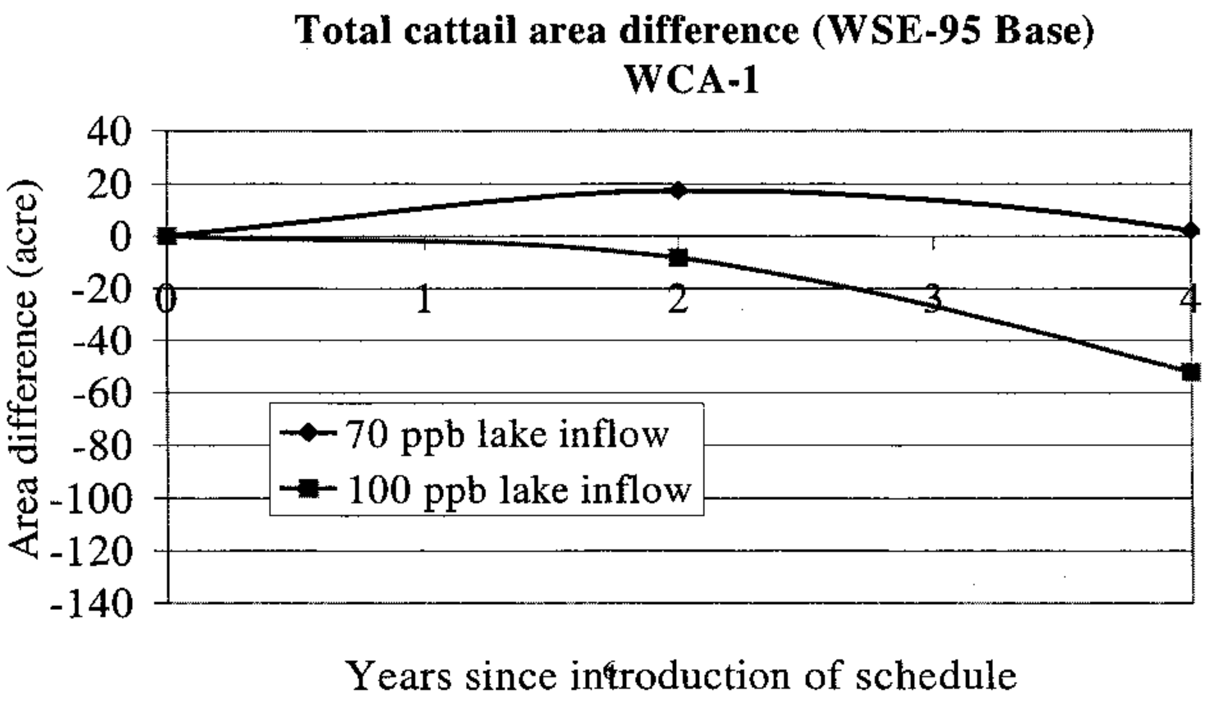
WCA 1 (Loxahatchee Wildlife Refuge)

The regulatory discharges that are directed through the West Palm Beach (through S-5A) and the Hillsboro canals (through S-6) have an impact on WCA1. The modeling also included any potential changes in basin runoff that are simulated for these basins.

The modeled loading ranges from 79.1 (70 ppb scenario) to 80.6 (100 ppb scenario) metric tons per year with the current schedule (Run 25; see Table 4). Because of the smaller volume of water with WSE, less phosphorus loading/year, relative to Run 25, is predicted. When "average annual" regulatory discharges are used, a decrease of 13,100 acre-ft/ year is predicted for WCA1 from the lake, and would result in a decrease in phosphorus loading of 1.4 metric tons/year relative to the simulated loading from Run 25. In this scenario, approximately 52 fewer acres of cattail spread, over a 4-year period, are predicted based on the EPGM, out of a total area of 145,920 acres for WCA 1 (Figure 2).

Discharges less than a full "average annual" would result in proportionately less benefit. The WSE schedule will rely on several factors including lake stage, hydrologic conditions north of the lake, and climatological predictions. Another positive impact may occur once STA1-W and STA2 are completed, as there is some flexibility to send regulatory discharges to these STAs.

Figure 2. Results of the EPG Model for WCA-1



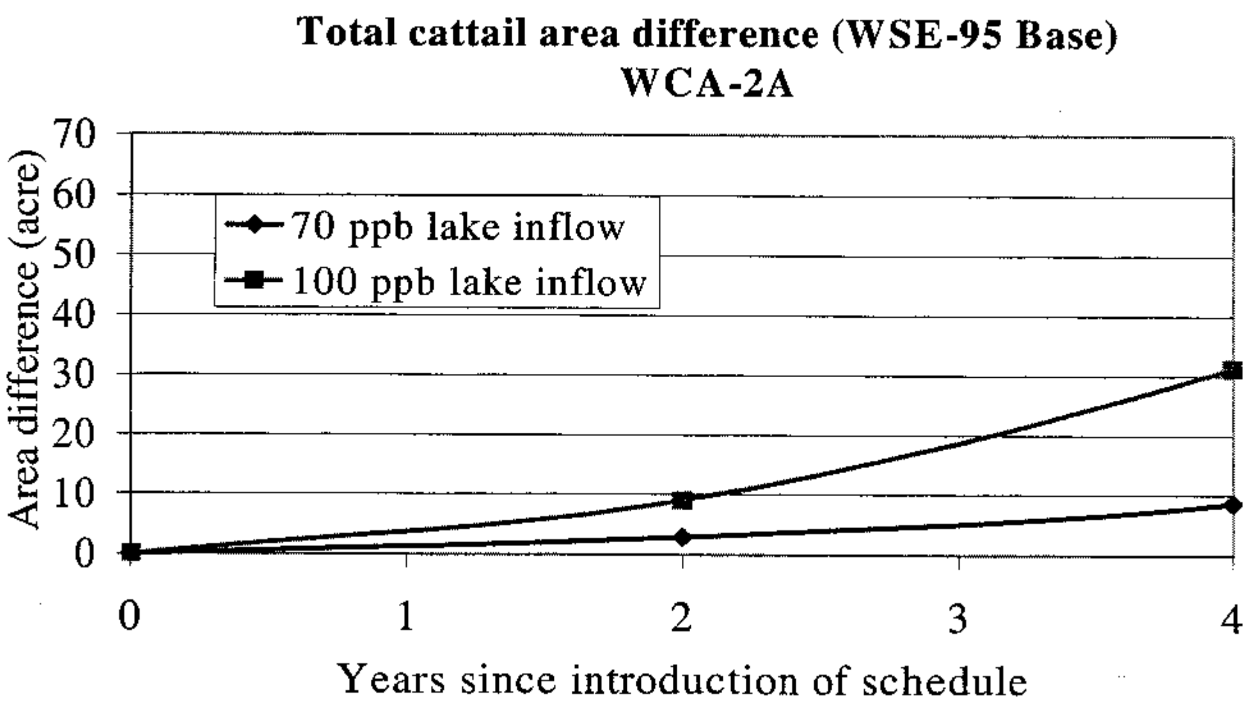
WCA 2A

The regulatory discharges that are directed through the North New River Canal (S-7) canal impact WCA 2A. The modeling also included any changes in basin runoff as a result of the WSE regulation schedule. For WCA 2A, STA 3/4 will be used. STA 3/4 will become fully operational on October, 2003. Therefore, approximately 4 years of regulatory discharges to the WCA 2A are possible, depending on the lake stage, hydrologic conditions north of the lake, and long-range climatological predictions that are part of the WSE regulation schedule.

The modeled loading ranges from 26.3 (70 ppb scenario) to 26.6 (100 ppb scenario) metric tons per year with the current schedule (Run 25; see Table 4). An additional 6,900 acre-ft/ year of flow is predicted with the WSE regulation schedule compared to Run 25. For 70 ppb, the closest scenario to the actual lake outflow in concentration, the cumulative effect over 4 years results in an increase of less than 9 acres in cattail coverage out of an area of 104,960 acres (Figure 3); the slight increase in cattails over the Run 25 schedule is due to a very slight increase in loading (0.6 tons/year more than Run 25) associated with the additional 6,900 acre-ft/yr of water.

In the worst case scenario, when 100 ppb outflow was used, well above the actual average shown in Table 1, the impact results in 0.9 additional metric ton per year, and a cumulative cattail increase of 31 acres greater than Run 25, based on results from the EPGM.

Figure 3. Results of the EPG Model for WCA-2

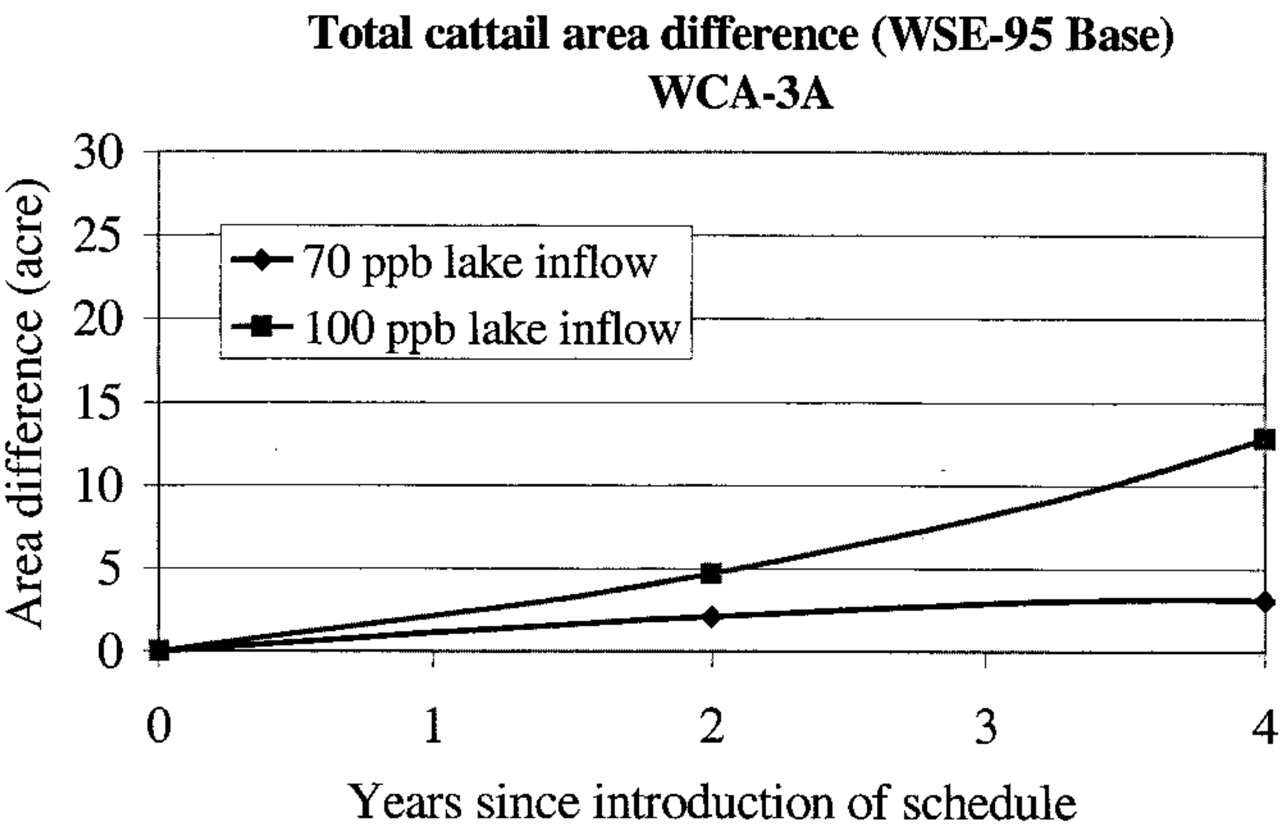


WCA 3A

The regulatory discharges that are directed through the Miami Canal (S-8) canal impact WCA 3A. As with the North New River canal, STA 3/4 will be used. STA 3/4 will become fully operational on October, 2003. Therefore, approximately 4 years of regulatory discharges to the WCA 3A are possible, depending on the lake stage, hydrologic conditions north of the lake, and long-range climatological predictions that are part of the WSE regulation schedule.

The modeled impact shows a slightly reduced concentration in total phosphorus with the WSE schedule compared to Run 25 (reduced from 110.6 ppb to 109 ppb when 70 ppb lake outflow is used). Because of the greater volume of water, 20,300 acre-ft/year, 1.8 additional metric tons/yr of phosphorus is predicted, an increase from 71.2 metric tons to 73 metric tons, with WSE compared to Run 25 (Table 4). In this realistic scenario, the cumulative effect over 4 years results in 7.2 metric tons of phosphorus that causes an increase in cattail by 3.1 acres out of an area of 494,080 acres (Figure 4).

Figure 4. Results of the EPG Model for WCA-3



Under the worst case scenario, when 100 ppb was used, a slightly reduced concentration in total phosphorus with the WSE schedule compared to Run 25 (reduced from 110.9 ppb to 110.4 ppb). The 100 ppb is well above the actual average shown in Table 1, and the impact results in 2.6 additional metric tons/yr compared to Run 25 (increases from 71.4 tons to 74 tons), with an increase of 13 acres more than the current schedule based on results from the EPGM.

Other Impacts:

In addition to the potential changes to the cattail in the WCAs, the area that becomes greater than 10 ppb is of concern. If these areas are currently occupied by periphyton communities, rather than emergent wetland plants, such as sawgrass, they can be impacted by the added phosphorus.

Table 5 summarizes the cattail area and the area that is simulated to become greater than 10 ppb as a result of the changes in flows from the WSE schedule. Note that the model is not sensitive enough to differentiate between the 70 and 100 ppb scenarios, especially considering the volume of lake water compared to basin runoff, for areas that become greater than 10 ppb.

Table 5. Summary of simulated net decrease/increase in cattail and area that becomes > 10 ppb in the WCAs (Run 25 -WSE).

	Inflow	**WCA1** acre	% of total	**WCA2** acre	% of total	**WCA3** acre	% of total
cattail	70 ppb	2	0.00	9	0.01	3	0.001
cattail	100 ppb	-52	-0.04	31	0.03	13	0.003
area>10ppb	70 ppb	-1087	-0.74	790	0.75	2134	0.432
area>10ppb	100 ppb	-1087	-0.74	790	0.75	2134	0.432

Conclusions:

The potential change in the WCAs' aquatic plant community is not significant, when these alternatives are compared, especially given 744,960 acre area of the WCAs. The difference between these two alternatives results in a change that is smaller than the accuracy of the modeling effort used to compare these alternatives.

Citation:

Implementation Strategies Towards The Most Efficient Water Management: The Lake Okeechobee WSE Operational Guidelines. February, 9, 1999. SFWMD and the USACE (DRAFT).

Walker, W.W. & R.H. Kadlec. 1996. A Model for Simulating Phosphorus Concentrations in Waters and Soils Downstream of Everglades Stormwater Treatment Areas, prepared for U.S. Department of Interior, Draft, August 13, 1996.

RES 01

MEMORANDUM

TO: Barry Rosen, Senior Supervising Environmental Scientist
Upper District Planning Division

FROM: Tom James, Senior Environmental Scientist,
Okeechobee Systems Research Division

THROUGH: Al Steinman, Director
Okeechobee Systems Research Division

SUBJECT: Water Quality Modeling of Lake Okeechobee Regulation Schedule Alternatives, Update

DATE: October 26, 1998

This is an update of a previous memo to Tom Teets dated August 1997: "Water Quality Modeling of Lake Okeechobee Regulation Schedule Alternatives." All model runs described below were resimulated because of improvements of the Lake Okeechobee Water Quality Model (LOWQM), and/or updates of outputs from the South Florida Water Management Model (SFWMM).

To determine the impact of alternative regulation schedules on water quality in Lake Okeechobee, I simulated one base and ten alternative regulation schedules using the one-box version of the LOWQM. I used monthly inflow, outflow, and evaporation data generated by the SFWMM for these alternative regulation schedules. The eleven regulation schedules were,

Run 25 1990
Run 25 2010
Run 25 PWS 2010
Run 22 AZE 1990
Run 22 AZE 2010
HSM 1990
HSM 2010
COE 1990
COE 2010
WSE 1990
WSE 2010

Run 25 2010 was used as the base simulation.

The one-box version of LOWQM computes lake wide averages for the various water quality components. As with all models, uncertainty exists in the predictions. This uncertainty results from representing a complex ecosystem such as Lake Okeechobee with a simplified model. For example, there are many algal groups in the lake with many different growth patterns that vary over groups, space, and time. The model represents only three algal groups with growth patterns defined by constant values, and this simplification produces model uncertainty.

This model is calibrated to observed data collected on the lake from 1973 to 1995. The information generated by SFWMM represents the time period from 1965 to 1995. To simulate the non-overlapping time period (1965-1972), I averaged time functions (e.g. sediment resuspension and settling, temperature, solar radiation) by month, over all years from the calibrated period (1973-1995) of LOWQM, excluding the hydrologic components. These mean values do not reflect any directional trends during this period, however they do encompass large variations in lake conditions from low water drought periods to high water flood periods. Therefore, the responses reflect an average of the conditions that the lake has experienced. Using these average values should not influence the outcome of the comparisons, because these values are not changed among the simulations, as described below.

The only changes made in the simulations are changes in inflow, outflow, and evaporation according to the data generated by the SFWMM. All other parameters and forcing functions remain the same because no a-priori reasons exist for changing them based on changes in the regulation schedule. Also any changes add a degree of uncertainty and could confound the results. Therefore, temperature, solar radiation, and resuspension and settling rates are the same in all simulations. All algal and nutrient kinetic parameters are the same in all simulations. Further documentation of the LOWQM can be found on the Central and Southern Florida Project Comprehensive Review Study Website:

"http://141.232.1.11./org/erd/osr/projects/lowqmweb/indexwq.html"

Because there have been both increases and decreases of inflow nutrient concentrations over time, and because changes cannot be accurately predicted into the future, these concentrations were set to constant values equivalent to 1990-1995 average flow weighted concentrations. I make this assumption to simulate current conditions into the future and to simplify the model simulations. Since nutrient loadings are highly correlated to inflow, using constant inflow concentrations have little impact on the final results. There is no information of changes in concentrations based on changes in the regulation schedule, thus these values remain constant over the different regulation schedules.

I made two comparisons of the base simulation to all other alternatives using yearly averages of total phosphorus (TP; Table 1) and chlorophyll *a* (CHLA; Table 2). I scored each alternative by determining the percent of years that the comparison value was less in the alternative than in the base scenario. Lower TP and CHLA concentrations are preferred and received higher scores because management goals for Lake Okeechobee include reduction of both parameters.

For TP, Run 22 AZE 1990, COE 1990, and HSM 2010 had the highest scores while Run 25 PWS, and HSM 1990 had the lowest scores (Table 1). For CHLA, HSM 1990, Run 25 1990, and COE 1990 had the highest scores, while Run 22 AZE 2010, COE 2010, and WSE 2010 had the lowest scores (Table 2). The different outcomes indicate both the complex interactions within the lake and uncertainty of model simulations.

The different outcomes can be explained, in part, by the impact of hydrology on TP and CHLA. Those regulation schedules with highest TP scores and lowest CHLA scores had lowest volumes and shallowest lake depth. Those with the lowest TP scores and highest CHLA scores had the highest volumes and greatest lake depth. Based on the model assumptions, shallow conditions allow for more TP to settle out which reduces the amount of TP in the water column. However, since the model assumes that the water column is homogenous in the vertical (as well as horizontal) dimension, shallow conditions provide more light per meter depth of the water column. This increased light per meter depth allows more phytoplankton growth and increases CHLA. Greater depths create the exact opposite conditions.

Based on this analysis, regulation schedules Run 22 AZE 1990, HSM 2010, and COE 1990 are preferred. Run 22 AZE 1990 and HSM 2010 also were recomended in the August 1997 memo to Tom Teets. However, this August 1997 memo did not recomend the COE 1990 simulation because it ranked 8th for TP and 4th for CHLA. In this update, COE 1990 ranked 2nd for TP and 3rd for CHLA. These differences in recomendations can be attributed to improvements in the calibration of the LOWQM and/or changes in the model simulation output for SFWMM that produced different simulations results.

Despite the substantial differences among these comparisons to the base simulation, the actual differences of TP and CHLA to the base simulation never exceeded 10 and 20 percent, respectively, on a yearly basis. The average yearly percent difference was much smaller (less than 2 percent for TP and 10 percent for CHLA). Because of the uncertainty in model predictions these values should be viewed with some caution. Further analysis is warranted before final recommendations can be made. This could include comparisons of light conditions, growth and biomass of algal groups, and amount of phosphorus available for algal uptake.

c: K. Havens
C. Neidrauer
T. Teets
T. Tisdale

Table 1. Percent of time alternative model run total phosphorus concentration is less than the base simulation (Run 25-2010) on a yearly averaged basis (31 years) and the average percent yearly difference between the base and comparison simulation.

Simulation	Years Below Base	Percent Years Below Base	Average Yearly Percent Difference from Base
Run 22 AZE 1990	29	93.55	-1.79
COE 1990	27	87.10	-1.00
HSM 2010	27	87.10	-0.43
Run 22 AZE 2010	26	83.87	-1.63
COE 2010	26	83.87	-0.68
WSE 1990	23	74.19	-0.79
Run 25 1990	23	74.19	-0.75
WSE 2010	22	70.97	-0.18
HSM 1990	16	51.61	-0.01
Run 25 PWS	10	32.26	0.06

Table 2. Percent of time alternative model run Chlorophyll *a* concentration is less than the base simulation (Run 25-2010) on a yearly averaged basis (31 years), and the average percent yearly difference between the base and comparison simulation.

Simulation	Years Below Base	Percent of Years Below Base	Average Yearly Percent Difference from Base
HSM 1990	31	100	-9.99
Run 25 1990	31	100	-6.19
COE 1990	31	100	-5.72
HSM 2010	30	96.77	-3.10
WSE 1990	29	93.55	-6.40
Run 22 AZE 1990	24	77.42	-3.85
Run 25 PWS	23	74.19	-0.13
WSE 2010	18	58.06	0.02
COE 2010	8	25.81	1.12
Run 22 AZE 2010	6	19.35	3.27

APPENDIX C

WSE IMPLEMENTATION PLAN

Final Report

Implementation Strategies Towards The Most Efficient Water Management:

The Lake Okeechobee WSE Operational Guidelines

The Operational Planning Core Team
April 12, 1999

South Florida Water Management District
3301 Gun Club Road
West Palm Beach, Florida, 33413

United States Army Corps of Engineers
400 West Bay Street
Jacksonville, Florida, 32232-0019

The Operational Planning Core Team Members:

Susan Bullock, USACE
Luis Cadavid
Dan Haunert
George Hwa
Kent Loftin
Ronald Mierau
Jayantha Obeysekera
Arlane Pankow
Everett R. Santee
Barry Rosen
Geoff Shaughnessy
Suzanne Sofia, USACE
Tommy Strowd
Eric Swartz
Beheen Trimble
Paul Trimble
Randy Vanzee
James Vearil, USACE
Cary White

Overview

In the original documentation of the simulations of alternative operational schedules for Lake Okeechobee (Neidrauer, Trimble, and Santee, 1998), the climate-based operational guidelines as incorporated in the WSE operation schedule emerged as a highly desirable approach to Lake Okeechobee water management. However, even in recognizing its apparent advantages, many questions and concerns were raised by the operational staffs of the South Florida Water Management District and the United States Army Corps of Engineers on the details of how such a schedule could be implemented. It has always been the intent of the WSE Operational Schedule developers that the entire spectrum of hydrologic, meteorologic and climatic data and forecasts be considered when implementing the WSE Operational Schedule. However, for simplicity sake and resource limitations that existed at the time of development, only the current water level and a six-month inflow forecast were used in the initial simulation of the WSE Operational Schedule. Since the time of the original documentation entitled *Simulation of Alternative Operational Schedules for Lake Okecchobee* was published, the Planning Department staff has met on a regular basis with the operational staff of the Operations and Maintenance Department and that of the United States Army Corp of Engineers to develop a detailed operational plan that could be safely implemented. This report is the product of these meeting.

The purpose of this report is to lay out the more specific operational guidelines that will allow for the successful implementation of the WSE Operational Schedule. These guidelines are quite explicit as we enter this new era of 'flexible' operations and climate based operational strategies. However, the enormous responsibility associated with Lake Okeechobee water management is clearly recognized such that this new era must be entered with the appropriate amount of caution. Therefore, it is the intent of this report to lay out clear guidelines for day to day operations while realizing that it may be appropriate to 'hedge' from these guidelines when unique environmental and hydrologic conditions present themselves. This shifting or 'hedging' should be done only after careful hydrologic analysis which demonstrates that such actions are truly desirable. Although emphasis has been placed on the water supply and environmental objectives in the development of the WSE schedule, the design and implementation of this operational schedule was completed in such a manner that it will also be a more proficient flood protection schedule. This is accomplished by including the hydrology of the vast tributary basin as an integral part of the decision making process and defining windows of opportunity that climate forecasts may be applied for substantial benefits and with minimum risk if a forecasted climate regime fails to materialize.

Introduction

It has been illustrated with the application of the South Florida Water Management Model (SFWMM; South Florida Water Management District, 1998) that flexible climate-based operational rules can facilitate a higher degree of proficiency for satisfying Lake Okeechobee water management objectives. (Neidrauer, Trimble,and Santee, 1998). These results were derived by integrating climate-based six-month inflow forecasts within the operational guidelines of the Water Supply and Environmental (WSE) Operational Schedule. This Operational Schedule allows for the water supply requirements to be satisfied at least as effectively as the current operational schedule (aka Run 25) while reducing the stress of prolonged high water levels on the littoral zone. The health of the littoral zone was originally the foremost reason for the revaluation of Lake Okeechobee Regulation Schedule. However, the 1997-1998 El Nino event illustrated that further refinements of the current operational schedule were desirable to minimize the adverse impacts to the estuaries. By incorporating the climate-based hydrologic forecasts, in addition to relieving the stress on the littoral zone, the simulated number of discharge events that adversely impact the St. Lucie and Caloosahatchee estuaries collectively were decreased while hydroperiods for the Everglades were enhanced.

In the actual implementation of the WSE Operational Schedule, it is suggested that additional hydrologic data, and the recent advances in hydro-meteorologic and climatologic forecasting be directly incorporated into the Lake Okeechobee operational guidelines. This report presents the most basic guidelines for implementation of the WSE Operational Schedule. It is expected, as new advances in hydrologic forecasting, modeling and analysis become available, innovative strategies should be investigated to apply these tools within the realm of the WSE Operational Guidelines.

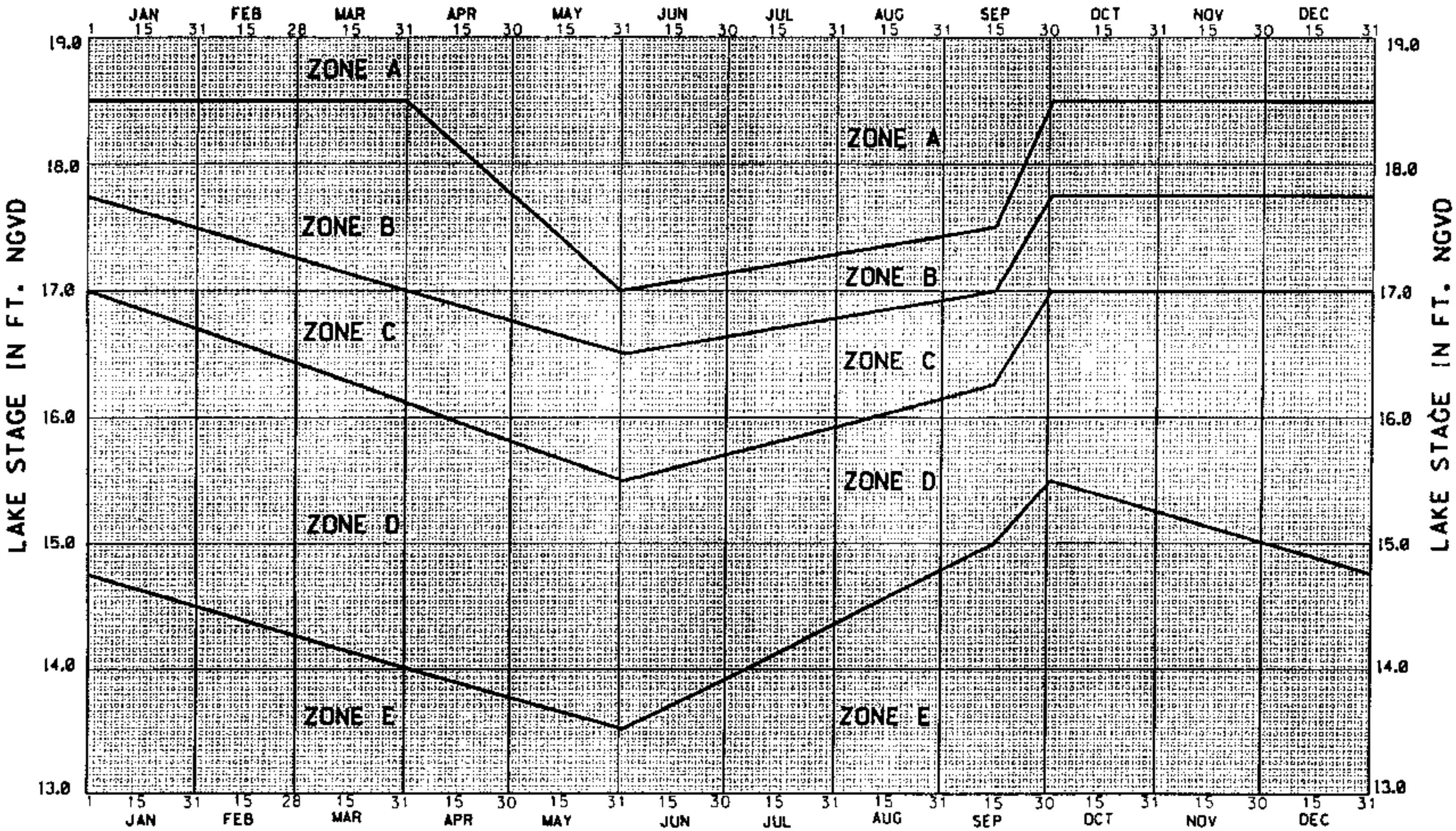
Essential WSE Operational Guidelines

Figure 1 illustrates the WSE Operational Schedule. This schedule promotes the amalgamation of our knowledge of the south Florida regional hydrologic system with that of the state and trends of the current global climate for operational proficiency. Figure 2a and 2b delineate detailed operational decision trees that will enable the successful implementation of the WSE schedule. Due to the approximate nature of extended climate forecasts, the extent of their application is proposed to be constrained by hydrologic conditions existing within the vast tributary basins. For example, it would not usually be deemed appropriate to only make minimum pulse releases in Zone B of the WSE Operational Schedule based on extended dry climate forecasts while very wet conditions exist in tributary basins and large inflows to the Lake are occurring. There will be times for 'hedging' from the basic WSE Operational Schedule implementation guidelines as unique hydrologic and/or environmental conditions present themselves in the future. However, even if no such hedging occurred, the WSE Operational Schedule is designed to lead to an advancement in operational proficiency by directly incorporating tributary hydrologic conditions and climate forecasts into the operational guidelines. In the following sub-sections the decision criteria (diamonds in the decision tree; Figure 2a and Figure 2b) are discussed in detail. These criteria may be considered the starting point from which to 'hedge' our operational decisions as unique hydrologic or environmental events present themselves.

Lake Okeechobee Water Level Criteria

Lake Okeechobee water levels should continue to be checked with a similar regularity as is procedure with the current operational schedule and at least as often as necessary to determine changes in the operational zone.

Figure 1



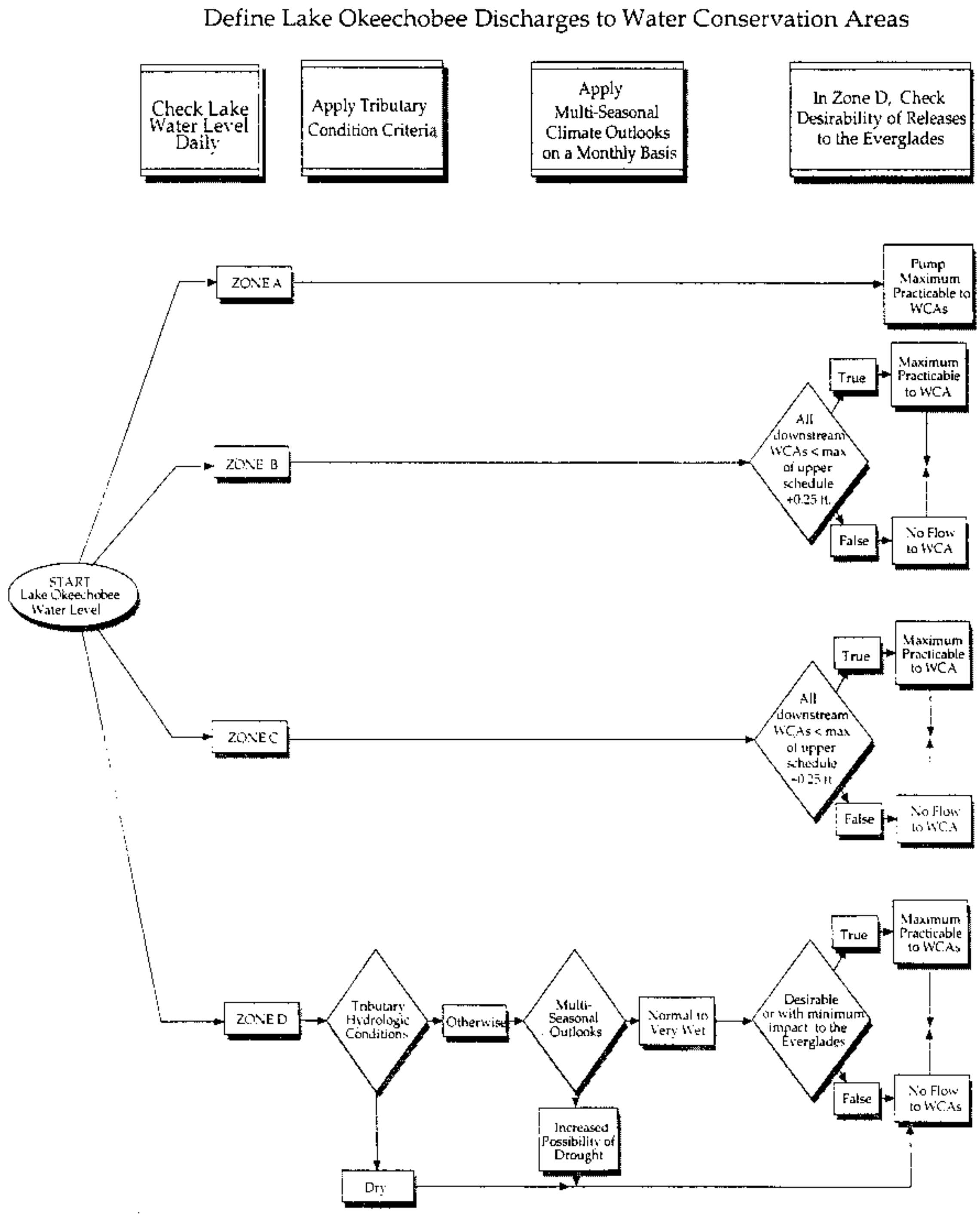
RELEASE THROUGH OUTLETS AS INDICATED

ZONE	AGRICULTURAL CANALS To WCAs (1)	CALOOSAHATCHEE RIVER AT S-77 (1,2,4)	ST. LUCIE CANAL AT S-80 (1,2,4)
A	PUMP MAXIMUM PRACTICABLE	UP TO MAXIMUM CAPACITY	UP TO MAXIMUM CAPACITY
B (3)	MAXIMUM PRACTICABLE RELEASES	NORMAL TO WET: UP TO 6500 CFS DRY: UP TO MAXIMUM PULSE RELEASE	NORMAL TO WET: UP TO 3500 CFS DRY: UP TO MAXIMUM PULSE RELEASE
C (3)	MAXIMUM PRACTICABLE RELEASES	WET: UP TO 4500 CFS NORMAL: UP TO MAXIMUM PULSE RELEASE DRY: NONE	WET: UP TO 2500 CFS NORMAL: UP TO MAXIMUM PULSE RELEASE DRY: NONE
D (3,5)	AS NEEDED TO MINIMIZE ADVERSE IMPACTS TO THE LITTORAL ZONE WHILE NOT ADVERSELY IMPACTING THE EVERGLADES. (SEE NOTE 5.)	VERY WET: UP TO MAXIMUM PULSE RELEASE OTHERWISE: NONE	VERY WET: UP TO MAXIMUM PULSE RELEASE OTHERWISE: NONE
E	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE

NOTES:
(1) SUBJECT TO FIRST REMOVAL OF RUNOFF FROM DOWNSTREAM BASINS
(2) GUIDELINES FOR WET, DRY AND NORMAL CONDITIONS ARE BASED ON: 1) SELECTED CLIMATIC INDICES AND TROPICAL FORECASTS AND 2) PROJECTED INFLOW CONDITIONS
(3) RELEASES THROUGH VARIOUS OUTLETS MAY BE MODIFIED TO MINIMIZE DAMAGES OR OBTAIN ADDITIONAL BENEFITS. CONSULTATION WITH EVERGLADES AND ESTUARINE BIOLOGISTS IS ENCOURAGED TO MINIMIZE ADVERSE EFFECTS TO DOWNSTREAM ECOSYSTEMS.
(4) PULSE RELEASES ARE MADE TO MINIMIZE ADVERSE IMPACTS TO THE ESTUARIES
(5) ONLY WHEN THE WCAs ARE BELOW THEIR RESPECTIVE SCHEDULES

DRAFT PROPOSED REGULATION SCHEDULE
LAKE OKEECHOBEE
SOUTH FLORIDA WATER MANAGEMENT DISTRICT
WEST PALM BEACH, FLORIDA
PROPOSED: 15 APRIL 1998
REVISED: 10 DECEMBER 1998
WSE

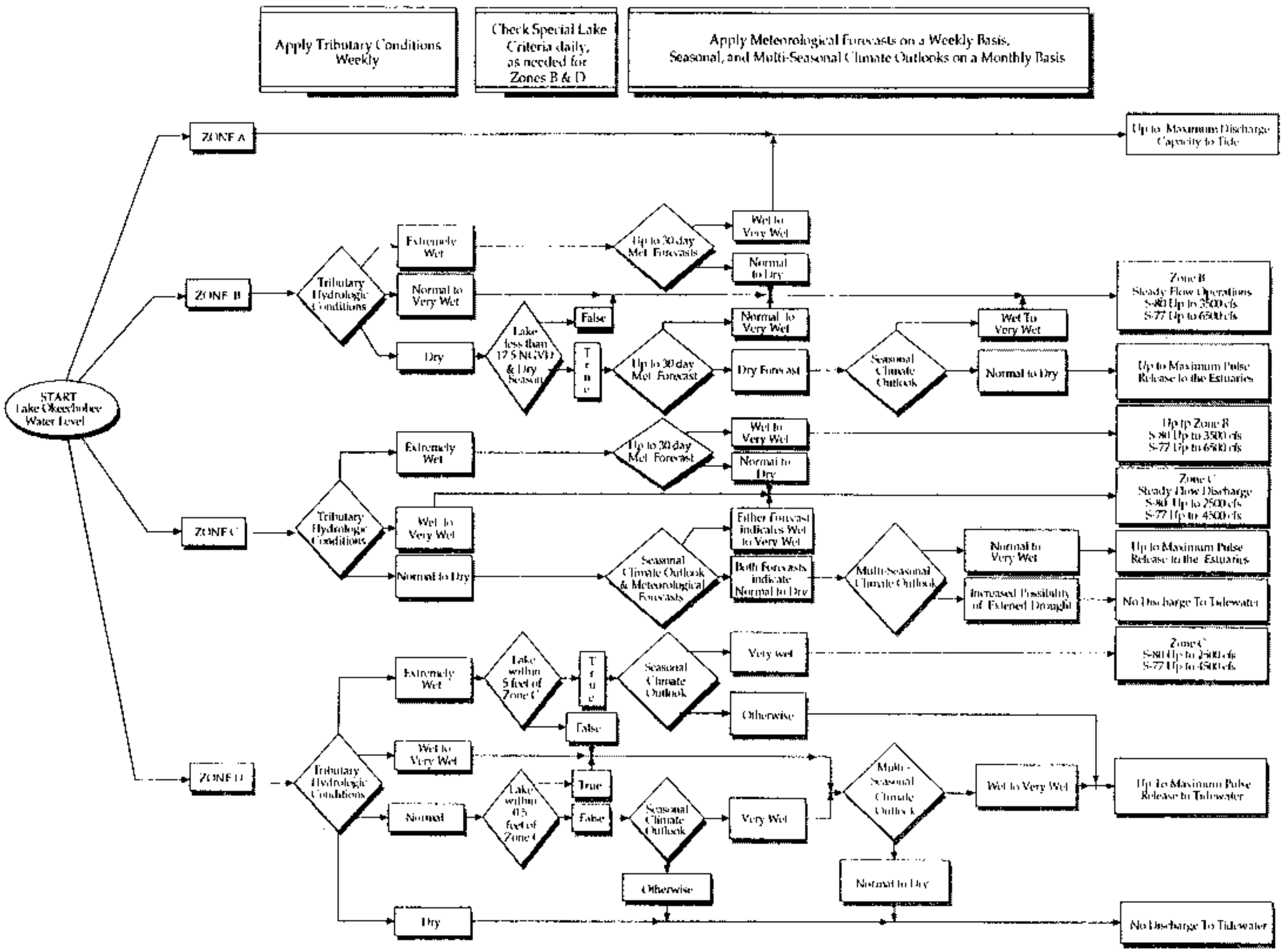
Figure 2a. WSE Operational Decision Tree



Hydrologic Analysis should be completed on a monthly basis for the purpose of identifying and evaluating Operational Alternatives to Unique Regional Hydrologic and/or Environmental conditions that may occure.

Figure 2b. WSE Operational Decision Tree

Define Lake Okeechobee Discharges to Tidewater



Hydrologic Analysis should be completed on a monthly basis for the purpose of identifying and evaluating Operational Alternatives to Unique Regional Hydrologic and/or Environmental conditions that may occur.

Tributary Hydrologic Conditions

The majority of the Lake Okeechobee regulatory schedules prior to 1978 (USACE, Rules and Operating Criteria Master Regulation Manuals, 1978) included operational flexibility. This allowed for adjustments to be made in the timing and magnitude of Lake Okeechobee regulatory discharges based on conditions in the Lake tributary basins and extended meteorological outlooks. The implementation of the WSE Operational Schedule suggest that such considerations be re-emphasized. These conditions will be especially valuable for determining whether the appropriate window of opportunity exists to 'hedge' water management practices in order to take advantage of the recent advances in climate forecasting. Two measures of the tributary hydrologic conditions are included within the design of the operational decision tree: 1) regional excess or deficit of net rainfall (rainfall minus evapotranspiration) during the past four weeks and, 2) the average S-65E inflow for the past two weeks. Each measure should be updated each week.

Thirty-Day Net Rainfall

The merit of the regional net rainfall may be derived from the following data sets:

1. the monthly rainfall record from the National Climatic Data Center (NCDC) for the period 1895-1998, and
2. the monthly evapotranspiration which was estimated as being 75% of the standard project storm ET for the Kissimme River Basin (USACE, 1978).

The net rainfall was computed by subtracting the monthly ET from the monthly rainfall for the period 1895 through May of 1998. The maximum, minimum, quartiles and 90th percentile of the net rainfall for each month is illustrated in Figure 3a. Figure 3b delineates the rainfall exceedance curve with all the months of the year being considered collectively. In the implementation of WSE schedule, it is recommended that the tributary rainfall data may be represented by averaging the upper and lower Kissimmee basins for the previous 30-day rainfall as made available in the South Florida Water Management District's (SFWMDs) daily weather report. The tributary basin ET may be represented as 60% of the long term daily average pan evaporation estimated at the Lake Alfred experimental station (on an annual average basis 60% of Lake Alfred Pan evaporation is equivalent to 75% of the standard project storm or about 44 inches per year). The net rainfall provides a valuable indicator of the regional hydrologic trends within the tributary basin during the past four weeks.

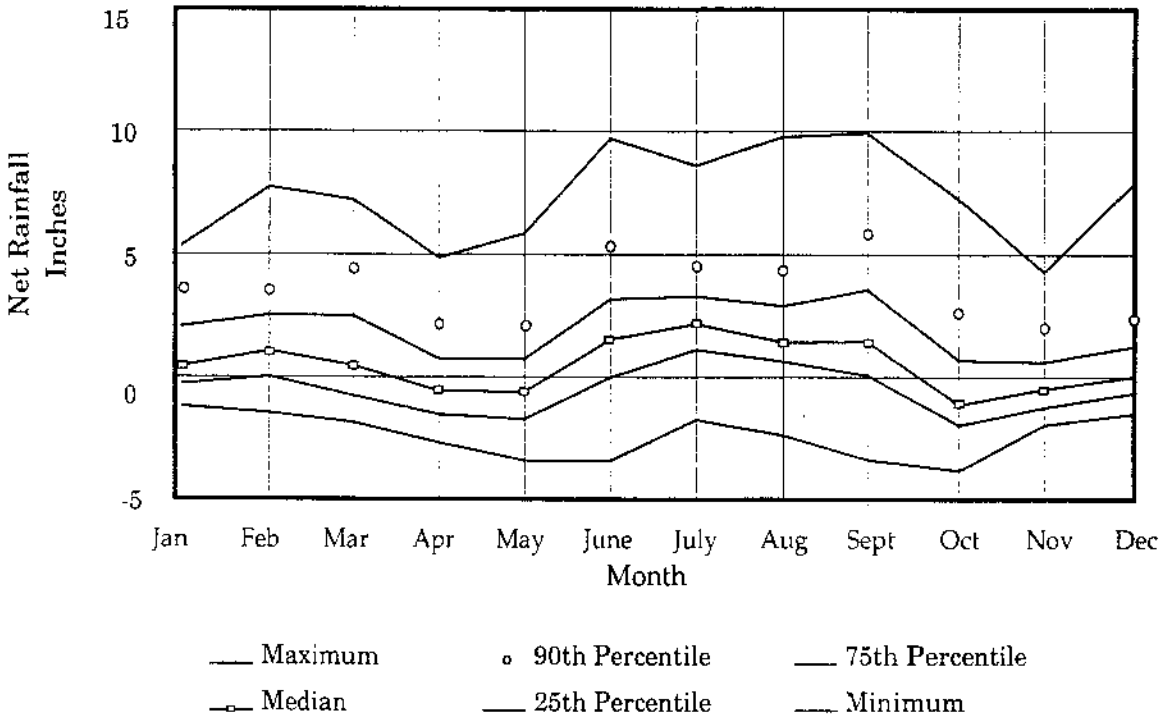
Two-Week Average S-65E Flow

The S-65E flow factors in the rainfall excesses or deficits that have accumulated within the Kissimmee tributary basins over periods of the past few days to periods for as long as several months. On average, S-65E flow represents between 35 to 50 percent of the structural inflows to Lake Okeechobee and thus is an additional effective regional hydrologic indicator of conditions in the tributary basin. Figure 4a and 4b summarize the statistics for the 14-day running average S-65E flow (the summary statistics consist of the maximum 14-day flow that occurred within each month) with a similar convention as was used for net rainfall. The period of record included in this analysis extends from 1930 through June of 1998. Sequential and ranked net rainfall and S-65E flows as computed for Figure 3 and Figure 4 are included in Appendices A, B, C and D, respectively.

Figure 3. Lake Okeechobee Tributary Net Rainfall Summary

Period of Analysis January 1895 - June 1998

(a) Monthly Quartiles and 90th Percentile



(b) Overall Monthly Net Rainfall-Frequency Curve

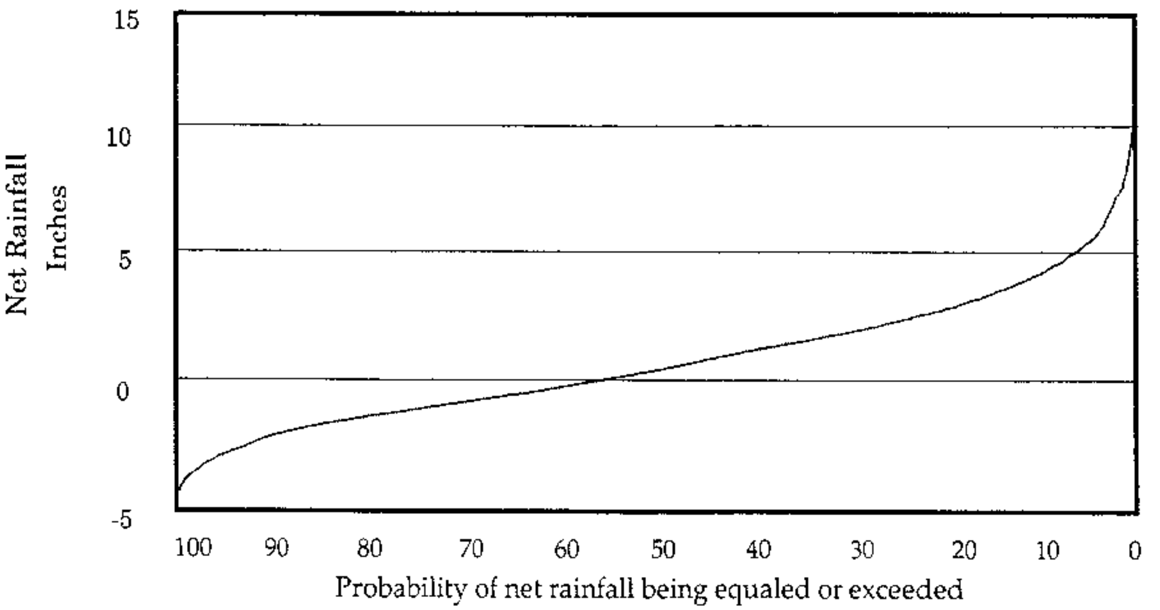
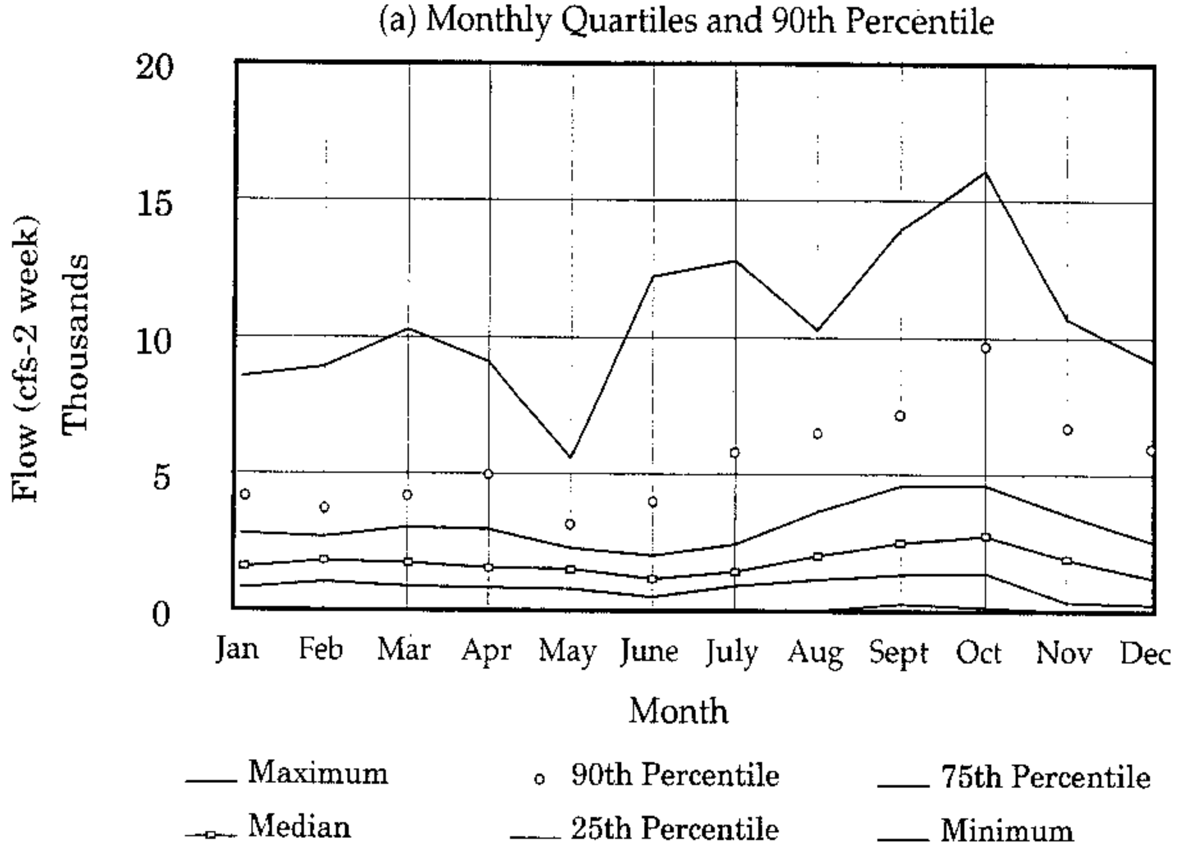
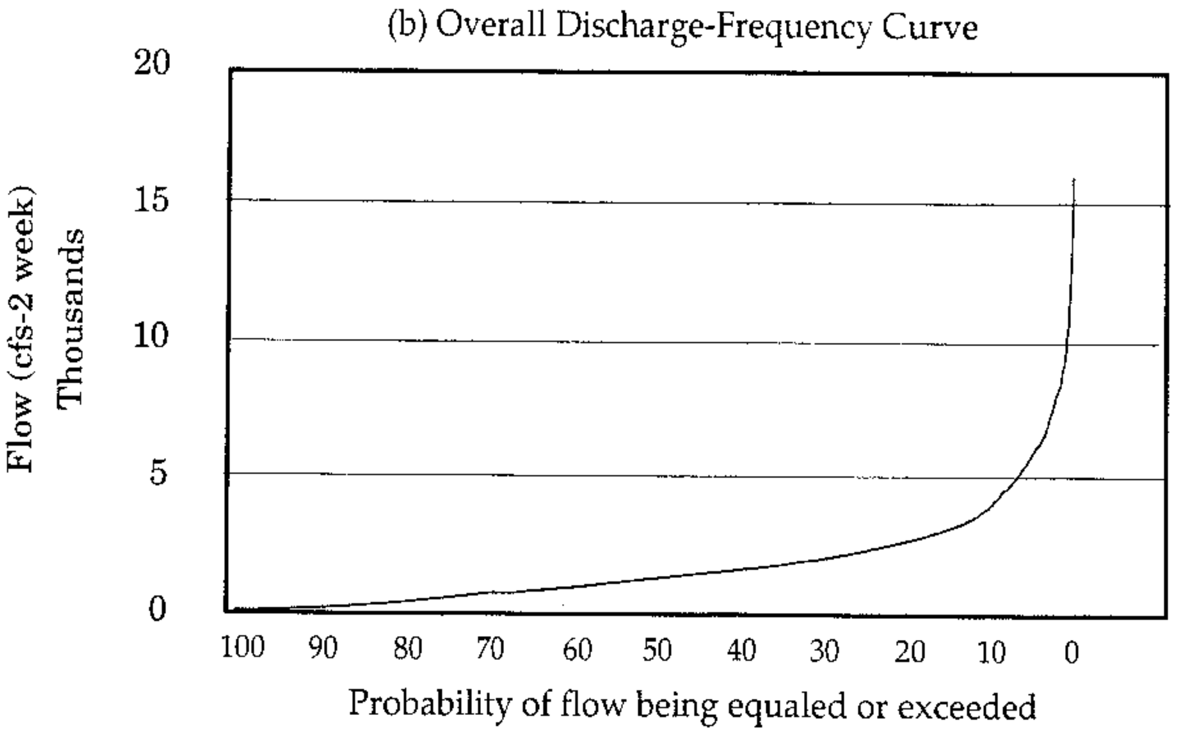


Figure 4. S-65E Historical Discharge Summary (cfs-2 week)

Period of Analysis January 1930 - June 1998





Identifying Various Hydrologic Regimes

Table 1 summarizes the ranges of the net rainfall and two-week average flow as they were selected to represent the various hydrologic regimes. These ranges were based on: 1. an extensive review of the available hydrologic record for the period beginning in 1930 and extending through the El Nino period of 1997-1998 and 2. testing with the application of the South Florida Water Management Model to determine the best threshold values for meeting the regional hydrologic performance measures. In this respect, each hydrologic classification are not specifically related to the mean or variances of the regional hydrologic indicator.

The wettest classification of the two regional hydrologic indicators is selected to represent the hydrologic conditions in the tributary basin to ensure that flood protection criteria are being met. Therefore, if net rainfall indicates wet conditions but S-65E flow indicates normal conditions, the operational condition will be taken to be 'wet'. During extreme wet conditions it is desirable to check regional hydrologic conditions every day. When conditions become extremely wet, there may be significant advantages for flood protection and environmental considerations to increase flows above the maximum flows rates defined for a given zone. This type of action should be taken only after the appropriate consideration has been given to all the primary water management objectives. When considering drier than normal conditions, both measures of tributary moisture should indicate dry conditions before tributary hydrologic conditions are defined to be 'dry'. The tributary hydrologic indicators should be updated weekly with a new value being computed for net rainfall and for average S-65E inflow each week.

Table 1. Classification of Tributary Hydrologic Regimes (Check weekly)[1]

Tributary Condition	Net Rainfall (inches past 4 weeks)	S-65E Flows (cfs-2 week average)
Very Dry	less than -3.00	less than 500
Dry	-3.00 - -1.01	500 - 1499
Normal	-1.00 - 1.99	1500 - 3499
Wet	2.00 - 3.99	3500 - 5999
Very Wet	4.00 - 7.99	6000 - 8999
Extremely Wet	greater than 8.0	greater than 9000

[1] Wet conditions are defined by the wettest of these two indicators.

Summary of Historical Rankings

Table 2 provides supporting hydrologic data for the classifications selected in Table 1. This data includes the percentage of weeks a particular hydrologic regime occurs and the average tributary basin net rainfall, S-65E flow and Lake net inflow for each regime. From this table, it can be recognized that under normal to dry tributary conditions, the Lake water levels can most often be successfully regulated with releases southward to the Everglades and/or low impact pulse releases to tidewater. For wet to very wet tributary conditions, normally larger steady flow discharges to tidewater will be required to control the Lake level. While for extremely wet conditions, larger flows, up to maximum capacity, may be required to control the Lake water levels. The exact magnitude of discharge required to tidewater is dependent on the Lake water level, whether the seasonal Lake operational schedule is rising or falling, the conveyance capacity for delivering excess water to the WCAs, the desirability or impact such releases would have on the Everglades, and finally the temporal and spatial distribution of the rainfall.

Hydrologic Conditions during the 1997-1998 El Nino

The WSE operational guidelines were designed in part based on the events of the 1997-1998 El Nino. This period includes by far the wettest dry season in the 103 years of record available for the Lake tributary basin. Areal average net rainfall of about 22 inches occurred over the Lake's vast tributary basin during the period of November 1, 1997 through March 31, 1998. This excess rainfall was more than twice as large as the second largest event that occurred during the 1982-1983 El Nino (November-March period). The 1982-1983 event had a net rainfall which was equivalent to about 10 inches of rain averaged over the Lake tributary basin. The current operational schedule (Run 25) was designed to lessen the impacts of an El Nino event such as that which occurred during the dry season of 1982-1983 with the tools available at that time but not a dry season rainfall as extreme as the 1997-1998 event. Complicating matters for

Table 2. Percentage of weeks that fall within each of the hydrologic regimes (based on the period of January 1930 through June 1998)

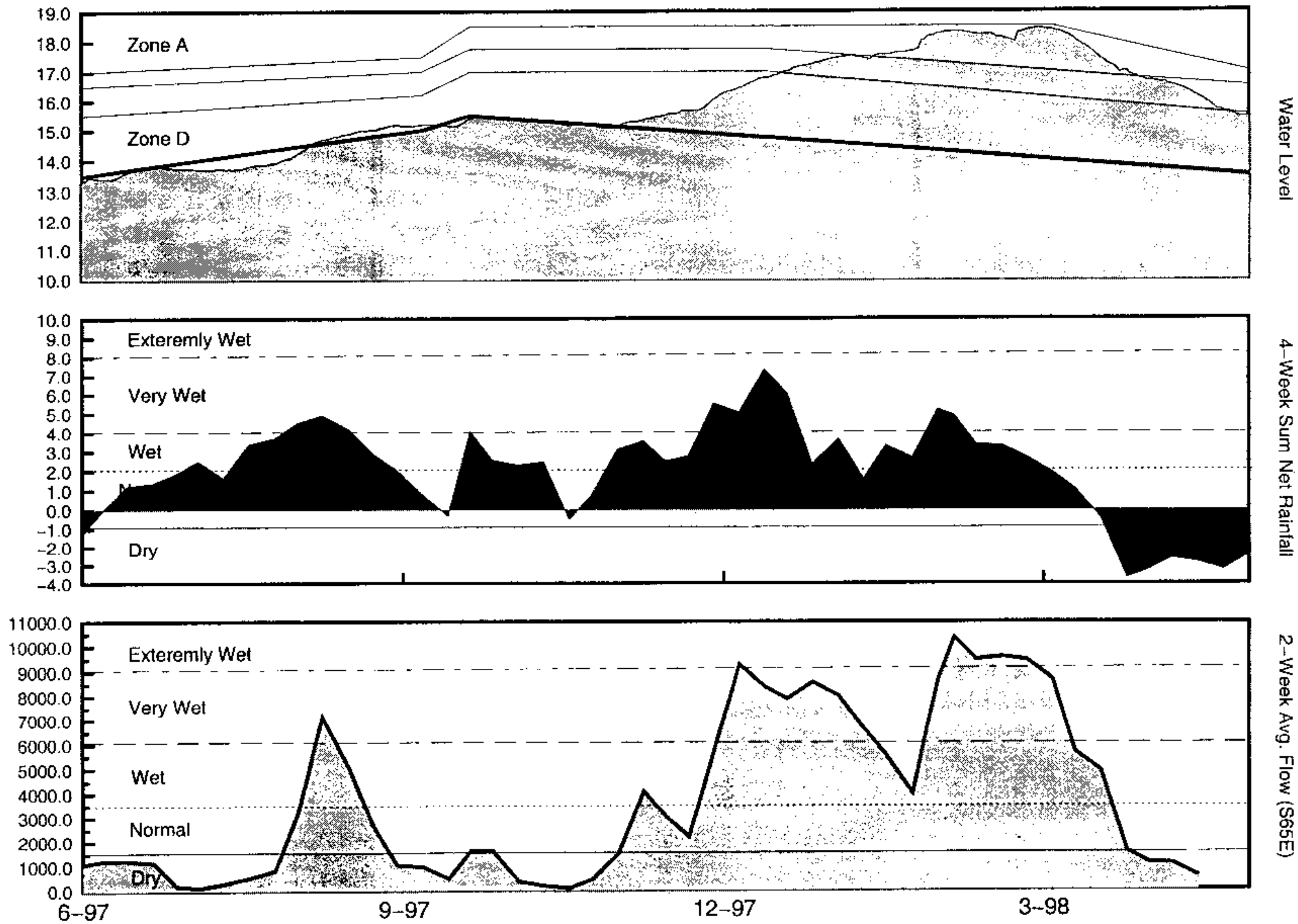
Tributary Conditions	Percent Occurrence	Average Net Rainfall (inches past 4 weeks)	Average S-65E Flow (cfs - 2 week average)	Average Net Lake Inflow (cfs - 2 week average)
Dry	21%	-2.2	580	1463
Normal	47%	0.1	1324	3236
Wet	19%	2.4	2344	5952
Very Wet	11%	4.7	3664	10007
Extremely Wet	2%	8.1	7929	16427

water management in south Florida was the fact that the last moderately strong El Nino (1991-1992) did not produce greater than normal rainfall. The WSE Operational Schedule would not recommend discharges during the 1991-1992 El Nino condition since the tributary basin remained relatively dry during this period. It does, however, allow for an earlier response at lower Lake levels during the 1997-1998 El Nino as the tributary conditions met the criteria of being 'very wet' by December 1997.

Figure 5 illustrates the Lake water levels relative to the WSE Operational Schedule during the 1997-1998 El Nino event. As the water levels in the Lake rose above the lowest line of the schedule in late November, net rainfall conditions already indicated the tributary basins were 'wet' and quickly becoming 'very wet'. This information, when combined with the Climate Prediction Center forecast for the likelihood of above normal rainfall, would have recommended the initiation of pulse releases to tidewater. Within the month of December of 1997, both net rainfall and S-65E flow conditions were indicative of 'extremely wet' conditions. During this period, while Lake water levels were in Zone D, it would have been desirable to initiate steady flow releases. Hydrologic conditions in the tributary basins remained extremely wet until the end of March. These conditions suggest that larger than the standard discharges in both Zones C and B would have been desirable in an attempt to decrease the duration of Zone A discharges. By mid-April, the tributary basins were in a drying state so that steady flow discharges were allowed to be reduced to pulse releases during the remainder of the dry season. A forecast of below normal rainfall for June of 1998 by the Climate Prediction Center and an increased potential for dry climate conditions for the 1998-1999 dry season suggested that it may be advantages to discontinue releases to tidewater during May, 1998. However, the passing of tropical storm Mitch in early November of 1998 eliminated potential advantages gained from this last action.

Another useful example of combining tributary hydrology with climate forecasts is the case of the spring and summer prior to a forecasted La Nina Year. During wet seasons months, based on the net rainfall computations for the tributary basins, conditions are normally classified as approaching or being wet during the period of June through September. However, during certain years the wet season may get a late start and/or never reach the normal wet conditions as defined in Table 1. Such combination of factors may lead to increased potential for drought especially if the following dry season is a La Nina year. Therefore, it may, at times, be desirable to discontinue or reduce regulatory discharges during the late spring months until the selected indicators suggest that a normal rainy season has begun. If conditions stay dry in the tributary basins, the Lake will decline to the desired levels by ET and water demands alone as the tropical season approaches. This will minimize impacts to the estuaries during a period of the year when large freshwater inflow are not normally desirable. This type of operational action should only be implemented in a way that ensures that Lake water levels does not exceed critical water levels during the peak of the hurricane season.

Figure 5. Hydrologic Indices for WSE Operational Schedule



Special Lake Okeechobee Water Level Criteria

Three special Lake Okeechobee water level criteria are included in the operational decision tree. These criteria are as follows:

1. Pulse releases are only permitted to replace steady flow releases during the dry season and when the Lake is below 17.5 feet.

2. When the Lake water levels are in the upper portion of Zone D, within .5 feet of Zone C, and normal conditions exist in the tributary basin, the decision to make pulse releases should be based on multi-seasonal forecasts,

3. While water levels are in Zone D, steady flow discharges due to extremely wet tributary basins are only suggested if the Lake water levels are within .5 feet of Zone C.

Higher than desirable water levels in the WCAs should allow pulse releases to be made to tidewater at lower Lake levels while lower than desired water levels in the WCAs may preclude or lessen regulatory discharges being made to tidewater. This is particularly true while water levels are in Zone D.

Seasonal Climatic and Meteorologic Outlooks

Changnon (1982) discussed possible uses of long range climate forecasts in water resources at the International Symposium on Hydrometorology sponsored by the American Water Resources Division. Although at the time of his presentation, climate forecasts may not have reached the point where they could be generally applied in water resources, his insights towards desired lead times and accuracy of forecasts needed for particular water resources applications still appear valid today. Changnon's paper has been included in Appendix E for ease of reference. With the recent advances in climate forecasting, it appears, with the appropriate caution, that the time for including these forecasts in the framework of the operational guidelines has arrived.

Due to the intricate and vast nature of the C&SF Flood Control Project and the complex interactions of tropical and extra-tropical weather system that effect Florida's weather, it should not be expected that extended forecasts can be made to a very precise level of accuracy. However, with recent advances in climate prediction, it is now possible to predict with some level of confidence whether the upcoming season is likely to have above, below or near normal rainfall. Changnon indicated that certain longer term regional water resources operational planning decisions can be enhanced by applying climate forecasts that are classified into three such terciles. It is at this level of detail at which the official seasonal forecasts[2] from the National Center of Environmental Predictions, Climate Prediction Center (CPC) are to be referenced in this application.

The year is partitioned into two seasons:

1. wet season (May-October) and
2. dry season (November-April)

The 3 to 6 month climate forecasts should be applied to make probabilistic hydrologic forecasts for the for the remainder of the current season. In addition to climate forecasts, when lake water levels are in Zone C or higher, one to two week meteorologic forecasts should also be considered.

Multi-seasonal Climate Outlooks
Multi-seasonal outlooks are applied to determine when an increased possibility of extended periods of abnormal rainfall may occur either in the form of large inflows to the Lake or increased potential for drought. When applying multi-seasonal climate forecasts for operational planning, it is important that the cumulative hydrologic effects be considered.

Tables of Additional Tools and Measures for WSE Implementation

There are several useful measures and tools that are currently available for Lake Okeechobee operational decisions. One of the most valuable sets of tools may be the regional hydrologic models that are available within the Hydrologic Systems Modeling Division of the Planning Department. These models are summarized in Table 3. Table 4 list additional meteorological and climate forecasts that may be considered.

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[2] http://nic.fb4.noaa.gov:80/products/predictions/multi_season/13_seasonal_outlooks /color/index.html)

Table 3. Regional Hydrologic Models

Models	Description	Contact
Object-Oriented Routing Model (ORM).	This model is initialized with current water levels and simulates water levels for a period of several months up to two years into the future considering climatological events that have occurred in the past. It is most useful in making probabilistic forecasts of expectation and setting confidence levels for these hydrologic projections when the climatology of the current year can be identified with a select class of past climatological years. For example, the 1998-1999 projected La Nina conditions may suggest that only the past La Nina years be considered when determining the expected value and confidence levels of these projection. This type of application is often referred to as 'position analysis'.	Cary White, Dr. Luis Cadavid, Dr. Jayantha Obeysekera and Randy Vanzee
South Florida Water Management Model (SFWMM)	This is the most well known regional hydrologic model. It's model domain includes from Lake Okeechobee, the Caloosahatchee River, and the St Lucie River Basins, southward through the Everglades and includes the Lower east Coast Developed Region. Currently this model is only applied for continuous simulation but may also be valuable tool if applied in the framework of position analysis	Dr. Luis Cadavid Paul Trimble Ray Santee
South Florida Regional Simulation Model (SFSRM)	This is the newest of the regional models that currently may be applied for the Everglades.	Randy Vanzee
Upper Kissimmee Lakes Model (UKISS)	This model simulates the Upper Kissimmee Lakes and may be useful for projecting flows through S-65 that will make their way through the Kissimmee River Basin to the Lake	Randy Vanzee

Table 4. Additional Climate Based Tools

Climate Tool	Description	Contact
Converting NOAAs Climate Forecasts to Statistical Hydrologic Forecasts	Thomas Croley (1996) presents an approach that applies historical hydrologic data together with the new long-lead climate forecasts, for making statistical hydrologic forecasts. The potential use of this methodology is currently under investigation by the Hydrologic Systems Modeling Division. Croley's paper appears in Appendix F.	Dr. Luis Cadavid Dr. Jayantha Obeysekera
Atlantic Ocean Thermohaline Current	Ongoing research of Colorado State University and the Atlantic Oceanographic and Meteorological Laboratory, have reported on cyclic decadal shifts of the Atlantic Ocean currents that significantly effect Climate regimes. within the Atlantic Ocean Basin. The most recent indicators of the phase of this ocean current indicates that Florida may expect much wetter conditions from June through October during the next few decades similar to those that were experienced during the decades of the 1930s, 1940s, 1950s and the 1960s.	Paul Trimble
Meteorological and Climatological Forecasts	SFWMD's Meteorological Forecasts	Geoff Shaughnessy, Eric P. Swartz
Solar Eruptive Activity and Secular Trends	Rainfall Activity seasonal to multi-seasonal prediction of shifts	Paul Trimble
Artificial Neural Networks, Intelligent Systems and other pattern recognition technology	Pattern recognition technology such as neural networks have provided another valuable tool for forecasting regional climate shifts for Florida that may best be explained by considering the state of El Nino, the Atlantic Ocean Thermohaline and solar activity together	Beheen Trimble Paul Trimble

Simulation of the WSE Implementation Plan

As a final step to this process, it is essential the detailed operational guidelines that were developed from this process are adequately tested. This is to ensure that they meet the regional water management objectives to a similar or greater level of proficiency as the original documented WSE simulation. This was accomplished with the application of the South Florida Water Management Model which was modified to incorporate the more detailed operational guidelines that are illustrated in Figure 2.

Baseline assumptions for this evaluation include:

1. Operation Schedule 25 (also referred to as Run 25),

2. 1995 infrastructure and water use levels,

3. Best Management Practices (BMPs) for the EAA,

4. BMP Replacement Water Rule is being applied,

5. 1995 Operational Schedules for the Water Conservation Areas,

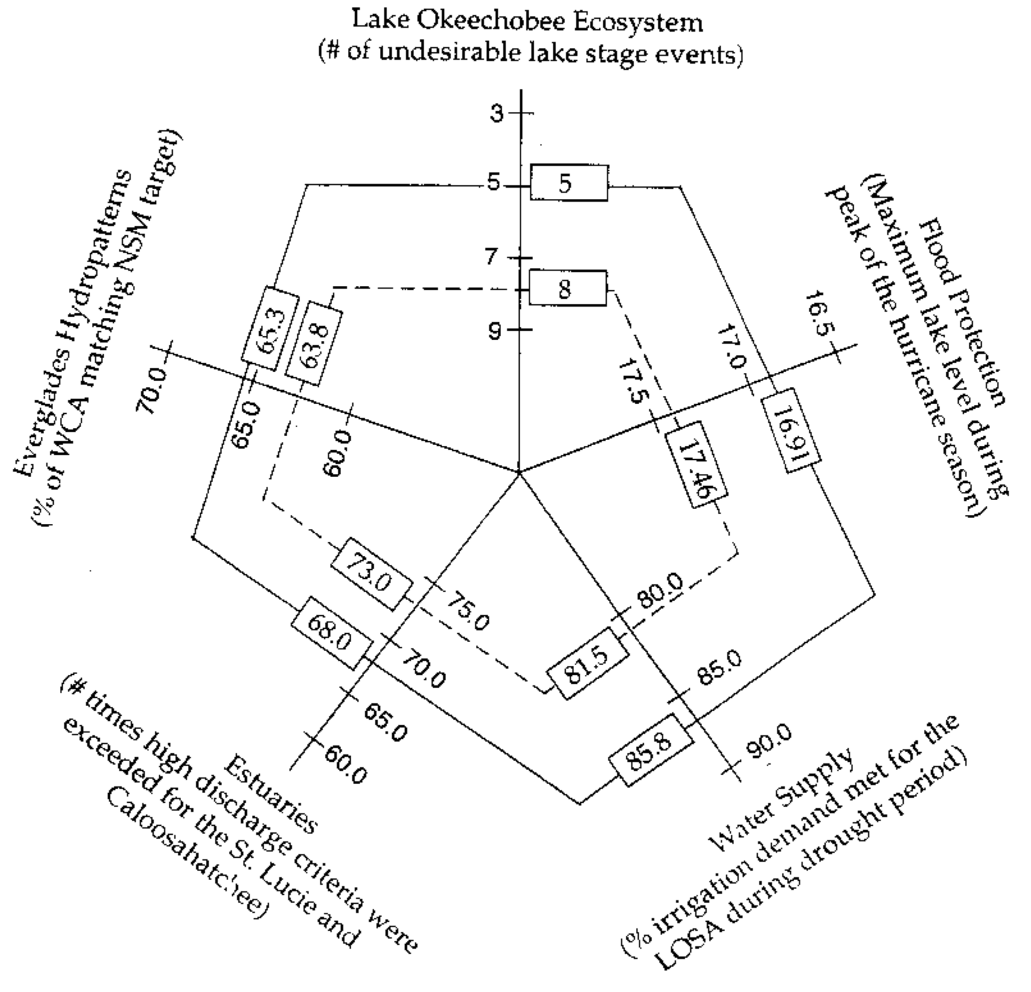
6. Additional constraints put on discharging regulatory releases to the WCAs when the Lake water levels are Zone B or C,

In the original simulations of the alternative operational schedules it was assumed that discharges to a particular WCA were discontinued when that WCA exceeded the maximum of its upper most schedule by more than .25 feet. This rule has been refined to discontinue the discharges if a particular WCA or any of the WCAs downstream the WCA under consideration are more than .25 feet above their schedule. For WCA2A, the maximum of the current drawdown schedule replaced the WCA2A regulatory schedule when making the operational decision whether regulatory discharges should be made from the Lake to the WCAs.

Simulated Results

A complete set of the performance measures, as presented in the original documentation of the alternative Lake Okeechobee Operational Schedule evaluation, are including in Appendix G. These performance measures are limited to comparing the 1995 base condition to that of the proposed WSE operational schedule. Figure 6 illustrates a similar trade-off analysis as was presented in the original report. The WSE operational schedule illustrates similar favorable performance measure trends as was previously documented. These include: 1) a decrease by 3 in the undesirable Lake Okeechobee water level events for the Lake littoral zone, 2) an increase by approximately 4 percent of the Lake Okeechobee Service Area water supply needs being met during drought years, 3) improved hydro-pattern matches to the Natural System

Figure 6. Multi-Objective Trade-Off Analysis



- - - - Operating Schedule 25(aka, Run 25)
——— Operating Schedule WSE

Axes designed so that larger pentagon represent better performance.

Model simulations within the WCAs, 4) a decrease in the number of times high discharge criteria were exceeded for the estuaries and 5) the simulated benefits for the estuaries and Everglades Hydroperiod. The benefits for the Everglades Hydroperiod appear to be reduced slightly due to the additional constraints that were discussed in the previous section for making regulatory releases to the WCAs. Finally, a crucial performance measure criterion is that for flood protection during the peak of the hurricane season. The number of days greater than 16.5 feet during the peak of the hurricane season (August 1-September 15th) was reduced from 47 days in the base condition to 6 days with the WSE Operational Schedule guidelines incorporated. The maximum water level for this same critical period of the year was reduced from 17.46 feet in the base condition to 16.91 feet with the WSE operational guidelines.

References

Neidrauer C.J., P.J. Trimble, E.R. Santee, Simulation of Alternative Operational Schedules for Lake Okeechobee, Hydrologic Systems Modeling Division, South Florida Water Management District, 1998

South Florida Water Management District, South Florida Water Management Model (SFWMM), 1998

Appendix A

Sequential Net Tributary Basin Rainfall
(inches)

Sequential Net Rainfall

1895	0.00	1.74	-0.40	1.41	0.00	-1.72	2.42	-0.30	0.41	-0.82	0.50	-0.58
1896	2.32	0.97	0.18	-2.48	-1.52	8.41	2.75	0.69	-0.09	-1.16	0.49	-0.22
1897	-0.05	4.11	-1.19	1.28	-1.67	0.51	2.04	1.25	8.41	-0.18	-0.43	0.49
1898	-1.13	0.65	-0.86	-2.16	-2.46	-2.71	3.41	7.86	0.04	0.18	-0.79	1.51
1899	2.64	4.09	-0.79	0.65	-3.16	1.55	4.37	1.25	1.31	1.39	-1.70	-0.19
1900	1.80	2.03	4.39	0.45	-0.03	2.62	2.50	-1.03	-0.43	0.69	-1.51	1.49
1901	0.10	2.64	2.80	-1.29	-0.48	6.99	1.62	5.13	3.58	-2.53	-1.32	-0.19
1902	-0.97	2.72	1.22	-1.37	-1.82	2.04	0.26	-0.99	4.92	0.71	0.50	1.04
1903	3.98	3.39	2.95	-2.67	0.15	1.15	1.79	1.34	3.73	-2.95	0.39	-0.25
1904	3.70	1.26	-0.55	-1.01	-1.68	2.47	1.29	1.56	0.26	1.20	0.44	-0.39
1905	-0.10	1.07	1.73	-0.58	1.13	-0.33	3.18	7.82	3.58	-1.95	-1.50	3.68
1906	2.05	1.29	0.06	-1.33	2.81	2.89	4.00	2.12	-2.00	-2.17	-1.18	-1.19
1907	-0.77	-0.64	-1.50	-0.32	0.18	1.58	2.79	0.65	3.04	-2.74	-0.75	2.68
1908	1.11	-0.04	-1.73	-0.69	-1.85	1.97	1.46	1.42	5.67	-1.39	-0.30	-1.23
1909	0.08	-0.63	-0.34	-0.78	-0.44	0.28	6.90	2.80	-0.82	-2.51	-1.33	0.35
1910	-0.70	1.54	0.18	-2.01	-2.05	4.96	2.34	4.24	-1.78	5.01	-0.43	-1.04
1911	-0.36	-1.47	0.23	-1.71	0.60	-0.30	0.90	3.86	-0.83	-0.32	1.49	1.40
1912	3.46	1.09	0.69	-0.05	1.63	8.66	0.29	0.04	5.14	-0.51	0.49	0.05
1913	0.15	3.14	2.34	-0.70	-1.06	-0.14	-0.01	1.82	-0.53	-1.84	-1.18	1.07
1914	3.05	3.34	-0.62	-0.67	-2.23	-1.26	0.95	-0.46	2.13	-1.54	-0.07	1.75
1915	3.48	2.20	0.55	-1.16	1.38	0.01	2.38	1.43	-0.53	1.54	0.23	0.01
1916	-0.36	-0.93	-1.17	-0.55	-0.41	1.66	0.27	0.97	0.40	-0.41	1.52	2.38
1917	-1.05	-0.42	-1.24	-1.61	-1.61	0.51	1.34	2.47	1.78	-1.57	-1.71	-0.41
1918	0.73	-1.01	0.87	1.89	-1.72	-0.21	0.43	0.34	1.23	0.81	0.58	0.68
1919	-0.02	2.89	2.74	-0.56	2.11	2.05	3.24	1.12	0.86	-2.49	1.12	0.11
1920	0.40	3.97	-1.65	2.13	0.60	1.37	1.98	0.40	3.63	-2.49	1.39	0.61
1921	-0.63	-0.33	-0.34	-1.47	1.65	-1.43	3.30	-1.60	-3.16	5.15	-0.11	0.28
1922	0.16	0.72	-0.94	-2.42	2.81	1.23	1.80	3.52	3.81	3.63	-0.58	0.23
1923	-0.44	-0.48	-0.51	-1.09	4.14	5.12	2.08	1.20	0.42	-0.38	-1.81	-0.85
1924	2.12	1.61	3.98	-0.49	-1.32	1.00	5.26	-1.25	4.29	7.24	-1.66	-0.41
1925	1.25	0.56	-0.17	-1.19	2.02	2.20	2.46	2.18	-2.80	-2.02	1.23	3.18
1926	3.35	0.31	1.70	1.87	-1.41	3.78	4.38	3.19	2.55	-1.77	0.50	-1.22
1927	-1.09	1.77	0.05	-1.53	-3.42	1.89	1.88	1.00	-0.41	-0.67	-1.05	-0.31
1928	-0.91	1.18	1.79	3.41	-0.81	-0.06	2.16	3.98	7.98	-1.46	-1.50	-0.47
1929	1.09	-0.71	-0.87	0.28	0.23	3.13	3.69	1.46	5.78	-1.75	-1.38	0.57
1930	1.46	1.77	5.06	0.56	-0.20	8.61	-0.90	-1.04	3.02	-1.84	0.57	1.74
1931	1.79	0.20	3.28	3.30	-0.50	-3.43	1.08	0.69	1.98	-2.09	-1.88	0.02
1932	-0.30	-0.99	0.64	-1.99	1.42	2.72	-1.74	4.83	0.52	-1.67	0.92	-1.48
1933	-0.12	1.54	0.76	3.42	-1.25	1.76	6.00	0.94	7.04	-0.94	-0.71	-1.50
1934	0.25	2.04	0.67	1.94	1.98	7.93	2.18	-0.85	1.08	-1.79	-1.57	-1.04
1935	-0.73	0.03	-1.67	1.12	-1.14	0.17	3.04	2.67	5.62	-1.59	-1.04	1.39
1936	2.71	6.45	1.17	-1.30	0.04	2.89	1.10	0.51	1.64	0.49	-0.28	-0.03
1937	-0.34	4.52	1.71	1.50	-0.82	0.91	3.10	2.59	-0.54	0.98	2.54	-0.73
1938	0.09	0.01	-0.80	-2.20	-0.61	1.54	3.69	-2.38	0.94	2.71	-0.77	-1.47
1939	-0.34	-0.77	-0.82	1.32	1.97	6.41	2.86	7.34	0.81	-1.36	-1.24	-0.60
1940	2.16	2.64	1.59	-0.76	-2.36	0.97	1.73	1.84	2.50	-3.78	-1.96	2.61
1941	2.83	2.07	0.87	2.70	-3.02	1.95	4.97	-0.43	1.13	-0.44	1.80	2.55
1942	1.45	2.65	3.06	0.10	-0.62	4.61	0.02	-0.11	0.54	-3.82	-1.69	1.25
1943	-0.45	-0.57	2.49	-1.11	0.44	4.65	4.94	3.34	1.04	-0.84	-0.72	-1.16
1944	0.02	-0.99	2.29	-0.14	-1.40	1.40	2.04	1.11	-1.15	2.56	-1.54	-1.36
1945	1.70	-1.17	-1.83	-1.10	-3.02	8.25	6.37	2.20	3.90	0.21	-0.78	1.23
1946	0.44	2.05	-0.53	-2.44	1.96	1.61	3.55	0.96	1.46	-1.22	-0.58	-0.91
1947	-0.16	2.65	4.37	1.45	0.23	4.10	4.24	2.54	8.13	-0.09	1.41	-0.07
1948	4.53	-0.60	0.54	1.[illegible]2	-1.42	-2.52	4.77	3.17	6.40	-1.28	-0.83	0.07
1949	-0.98	-0.63	-1.31	0.09	-2.24	3.18	1.13	9.78	3.86	-1.78	-0.53	0.55
1950	-1.21	-0.97	1.09	-0.71	-1.80	-0.92	2.40	1.03	3.31	2.33	-1.27	1.59
1951	-0.92	0.85	-0.73	4.85	-2.51	-0.86	2.84	1.10	2.83	-0.16	1.91	-0.34
1952	-0.10	3.21	2.90	-1.72	-0.62	-1.83	2.13	1.80	0.48	5.15	-0.49	-0.59
1953	1.49	1.33	1.36	1.82	-3.03	4.67	1.90	3.69	6.15	1.69	3.19	2.14

Sequential Net Rainfall

1954	0.04	0.41	-0.66	1.14	1.70	2.42	2.71	-0.03	2.03	-1.53	1.48	-0.26
1955	1.07	0.17	0.12	-0.85	-1.75	0.55	2.25	1.11	0.90	-1.41	-0.67	-0.12
1956	-0.27	-0.17	-1.87	-0.03	-0.74	-1.12	0.37	1.48	1.58	3.29	-1.59	-1.30
1957	0.87	2.53	2.68	3.76	3.38	1.40	3.22	3.65	4.17	-1.12	-0.45	0.76
1958	5.32	1.78	3.75	0.56	-0.14	-0.00	0.29	0.30	-0.63	0.41	-0.48	2.24
1959	1.99	1.39	7.20	0.79	2.37	4.79	2.60	3.75	3.60	3.72	-0.31	0.30
1960	-0.27	3.39	5.82	0.61	-1.34	1.00	8.61	0.65	9.93	-0.84	-1.61	-0.47
1961	1.21	0.99	0.07	-0.53	-0.04	-0.66	-0.16	2.07	-2.07	-2.78	-1.09	-0.18
1962	-0.06	-0.38	1.21	-0.29	-1.31	4.36	0.79	4.21	4.73	-3.04	0.52	-1.17
1963	0.77	5.55	-0.36	-2.48	1.39	1.07	1.58	-0.25	3.28	-3.01	3.34	1.47
1964	2.56	3.57	0.88	-1.14	-0.93	-0.95	1.73	2.10	1.35	-1.82	-1.23	0.37
1965	-0.12	2.30	0.75	-1.21	-3.33	2.95	5.37	1.12	0.97	-0.28	-1.09	0.42
1966	3.86	2.87	-0.77	-0.46	-0.13	4.03	1.32	1.57	1.09	-1.60	-1.60	-0.66
1967	-0.26	2.34	-1.45	-2.68	-2.97	2.52	2.87	4.82	-0.26	-1.96	-1.71	0.64
1968	-0.83	0.48	-1.20	-2.09	1.56	9.04	3.16	0.61	0.65	0.66	0.75	-1.21
1969	1.21	0.24	4.59	-1.54	0.64	1.07	1.45	3.84	2.42	2.50	0.61	2.33
1970	2.07	1.38	4.24	-2.38	0.55	-0.48	0.77	0.65	0.67	-1.44	-1.27	-0.91
1971	-0.78	2.52	-0.84	-1.96	-0.87	0.07	2.41	2.92	1.87	1.19	-0.20	-0.08
1972	-0.22	3.49	0.47	-1.05	-0.20	2.79	-1.44	1.87	-3.39	-1.62	1.98	0.82
1973	4.12	0.77	1.15	0.65	-1.30	-0.02	4.05	1.87	2.72	-2.36	-0.72	1.23
1974	-0.76	-0.12	-0.98	-1.68	-0.71	8.53	3.76	1.71	0.81	-3.61	-1.51	0.70
1975	-0.47	0.78	-1.00	-1.89	1.37	1.09	3.05	0.93	2.64	1.15	-1.10	-0.98
1976	-0.73	-0.81	-1.09	-0.92	4.51	2.77	0.48	1.04	1.91	-2.75	0.08	0.61
1977	0.95	0.41	-1.42	-2.24	-1.27	-0.11	2.00	2.11	2.00	-2.43	0.98	2.51
1978	1.48	2.49	0.60	-2.26	0.81	2.27	4.25	0.42	-1.00	-1.94	-1.22	2.21
1979	5.07	0.13	-0.13	-1.36	5.84	-1.39	0.71	3.13	9.05	-3.42	-0.40	0.35
1980	1.55	1.07	0.04	0.74	0.65	-1.12	0.96	0.17	-0.18	-2.61	1.83	-0.66
1981	-0.80	2.19	-1.02	-2.69	-1.79	1.97	-0.42	6.18	0.47	-2.96	-0.35	0.06
1982	0.28	0.99	4.26	1.07	1.92	5.07	2.42	1.32	3.96	-0.89	0.21	-0.63
1983	1.51	7.71	4.60	-0.47	-1.90	1.70	1.14	2.39	1.65	1.09	0.61	4.03
1984	-0.07	1.84	0.67	-0.49	0.74	-1.13	3.70	0.54	0.09	-3.21	1.76	-1.23
1985	-0.08	-0.55	0.24	-0.30	-2.16	1.02	1.68	2.40	2.91	-1.15	-0.34	-0.06
1986	1.64	0.42	2.20	-2.25	-2.17	4.16	1.38	1.89	-0.52	2.16	-0.54	1.67
1987	1.47	0.34	6.94	-2.41	0.26	0.17	1.60	-0.60	1.05	-0.20	4.29	-1.30
1988	1.34	0.80	2.89	-1.57	-1.20	-1.22	2.83	3.17	3.20	-3.14	2.81	-0.42
1989	1.12	-1.05	0.42	-0.48	-2.46	0.86	1.39	0.86	2.61	-1.13	-0.60	2.27
1990	-0.67	2.17	-1.12	-1.12	-1.22	1.23	3.65	1.90	-0.49	-0.30	-0.87	-1.05
1991	2.49	0.31	2.64	1.83	3.18	1.40	5.26	1.16	-1.14	-1.17	-1.44	-1.16
1992	0.05	2.73	-0.41	1.01	-2.73	9.71	-1.10	3.71	1.05	-1.28	1.47	-0.76
1993	4.96	1.04	3.31	0.70	-1.25	-1.73	-0.01	0.93	1.03	1.23	-0.88	-0.54
1994	2.69	0.98	-0.11	0.70	-1.85	3.65	1.92	2.74	5.03	-0.08	1.98	1.96
1995	1.34	0.77	-0.01	0.50	-1.93	4.50	4.41	5.84	2.30	3.68	-0.19	-1.00
1996	3.41	0.34	4.70	-0.66	0.44	2.64	-0.93	-0.04	-0.19	0.20	-1.23	0.66
1997	0.58	-0.07	-0.08	4.33	-0.95	0.92	2.53	1.10	2.91	-1.13	3.68	7.80

Appendix B

Ranked Net Tributary Basin Rainfall
(inches)

Ranked Net Rainfall

January		February		March		April		May		June		July		August		September		October		November		December	
1958	5.32	1983	7.71	1959	7.20	1951	4.85	1979	5.84	1992	9.71	1960	8.61	1949	9.78	1960	9.93	1924	7.24	1987	4.29	1997	7.80
1979	5.07	1936	6.45	1987	6.94	1997	4.33	1976	4.51	1968	9.04	1909	6.90	1898	7.86	1979	9.05	1921	5.15	1997	3.68	1983	4.03
1993	4.96	1998	6.40	1960	5.82	1957	3.76	1923	4.14	1912	8.66	1945	6.37	1905	7.82	1897	8.41	1952	5.15	1963	3.34	1905	3.68
1948	4.83	1963	5.55	1930	5.06	1933	3.42	1957	3.38	1930	8.61	1933	6.00	1939	7.34	1947	8.13	1910	5.01	1953	3.19	1925	3.18
1973	4.12	1937	4.52	1996	4.70	1928	3.41	1991	3.18	1974	8.53	1965	5.37	1981	6.18	1928	7.98	1959	3.72	1988	2.81	1907	2.68
1903	3.98	1897	4.11	1983	4.60	1931	3.30	1906	2.81	1896	8.41	1924	5.26	1995	5.84	1933	7.04	1995	3.68	1937	2.54	1940	2.61
1966	3.86	1899	4.09	1969	4.59	1941	2.70	1922	2.81	1945	8.25	1991	5.26	1901	5.13	1948	6.40	1922	3.63	1972	1.98	1941	2.55
1904	3.70	1920	3.97	1900	4.39	1920	2.13	1959	2.37	1934	7.93	1941	4.97	1932	4.83	1953	6.15	1956	3.29	1994	1.98	1977	2.51
1915	3.48	1964	3.57	1947	4.37	1934	1.94	1919	2.11	1901	6.99	1943	4.94	1967	4.82	1929	5.78	1938	2.71	1951	1.91	1916	2.38
1912	3.46	1972	3.49	1998	4.27	1918	1.89	1925	2.02	1939	6.41	1948	4.77	1910	4.24	1908	5.67	1944	2.56	1980	1.83	1969	2.33
1996	3.41	1903	3.39	1982	4.26	1926	1.87	1934	1.98	1923	5.12	1995	4.41	1962	4.21	1935	5.62	1969	2.50	1941	1.80	1989	2.27
1926	3.35	1960	3.39	1970	4.24	1991	1.83	1939	1.97	1982	5.07	1926	4.38	1928	3.98	1912	5.14	1950	2.33	1984	1.76	1958	2.24
1998	3.26	1914	3.34	1924	3.98	1953	1.82	1946	1.96	1910	4.96	1899	4.37	1911	3.86	1994	5.03	1986	2.16	1916	1.52	1978	2.21
1914	3.05	1952	3.21	1958	3.75	1937	1.50	1982	1.92	1959	4.79	1978	4.25	1969	3.84	1902	4.92	1953	1.69	1911	1.49	1953	2.14
1941	2.83	1913	3.14	1993	3.31	1947	1.45	1954	1.70	1953	4.67	1947	4.24	1959	3.75	1962	4.73	1915	1.54	1954	1.48	1994	1.96
1936	2.71	1919	2.89	1931	3.28	1895	1.41	1921	1.65	1943	4.65	1973	4.05	1992	3.71	1924	4.29	1899	1.39	1992	1.47	1914	1.75
1994	2.69	1966	2.87	1942	3.06	1939	1.32	1912	1.63	1942	4.61	1906	4.00	1953	3.69	1957	4.17	1993	1.23	1947	1.41	1930	1.74
1899	2.64	1992	2.73	1903	2.95	1897	1.28	1968	1.56	1995	4.50	1974	3.76	1957	3.65	1982	3.96	1904	1.20	1920	1.39	1986	1.67
1964	2.56	1902	2.72	1952	2.90	1954	1.14	1932	1.42	1962	4.36	1984	3.70	1922	3.52	1945	3.90	1971	1.19	1925	1.23	1950	1.59
1991	2.49	1942	2.65	1988	2.89	1935	1.12	1963	1.39	1986	4.16	1938	3.69	1943	3.34	1949	3.86	1975	1.15	1919	1.12	1898	1.51
1896	2.32	1947	2.65	1901	2.80	1982	1.07	1915	1.38	1947	4.10	1929	3.69	1926	3.19	1922	3.81	1983	1.09	1977	0.98	1900	1.49
1940	2.16	1901	2.64	1919	2.74	1948	1.02	1975	1.37	1966	4.03	1990	3.65	1988	3.17	1903	3.73	1937	0.98	1932	0.92	1963	1.47
1924	2.12	1940	2.64	1957	2.68	1992	1.01	1905	1.13	1926	3.78	1946	3.55	1948	3.17	1920	3.63	1918	0.81	1968	0.75	1911	1.40
1970	2.07	1957	2.53	1991	2.64	1959	0.79	1978	0.81	1994	3.65	1898	3.41	1979	3.13	1959	3.60	1902	0.71	1969	0.61	1935	1.39
1906	2.05	1971	2.52	1943	2.49	1980	0.74	1984	0.74	1949	3.18	1921	3.30	1971	2.92	1901	3.58	1900	0.69	1983	0.61	1942	1.25
1959	1.99	1978	2.49	1913	2.34	1994	0.70	1980	0.65	1929	3.13	1919	3.24	1909	2.80	1905	3.58	1968	0.66	1918	0.58	1945	1.23
1988	1.84	1967	2.34	1944	2.29	1993	0.70	1969	0.64	1965	2.95	1957	3.22	1994	2.74	1950	3.31	1936	0.49	1930	0.57	1973	1.23
1900	1.80	1965	2.30	1986	2.20	1899	0.65	1911	0.60	1936	2.89	1905	3.18	1935	2.67	1963	3.28	1958	0.41	1962	0.52	1913	1.07
1931	1.79	1915	2.20	1928	1.79	1973	0.65	1920	0.60	1906	2.89	1968	3.16	1937	2.59	1988	3.20	1945	0.21	1926	0.50	1902	1.04
1945	1.70	1981	2.19	1905	1.73	1960	0.61	1970	0.55	1972	2.79	1937	3.10	1947	2.54	1907	3.04	1996	0.20	1895	0.50	1972	0.82
1986	1.64	1990	2.17	1937	1.71	1930	0.56	1943	0.44	1976	2.77	1975	3.05	1917	2.47	1930	3.02	1898	0.18	1902	0.50	1957	0.76
1980	1.55	1941	2.07	1926	1.70	1958	0.56	1996	0.44	1932	2.72	1935	3.04	1985	2.40	1997	2.91	1994	-0.08	1912	0.49	1974	0.70
1983	1.51	1946	2.05	1940	1.59	1995	0.50	1987	0.26	1996	2.64	1967	2.87	1983	2.39	1985	2.91	1947	-0.09	1896	0.49	1918	0.68
1953	1.49	1934	2.04	1953	1.36	1900	0.45	1947	0.23	1900	2.62	1939	2.86	1945	2.20	1951	2.83	1951	-0.16	1904	0.44	1996	0.66
1978	1.48	1900	2.03	1902	1.22	1929	0.28	1929	0.23	1967	2.52	1951	2.84	1925	2.18	1973	2.72	1897	-0.18	1903	0.39	1967	0.64
1987	1.47	1984	1.84	1962	1.21	1942	0.10	1907	0.18	1904	2.47	1988	2.83	1906	2.12	1975	2.64	1987	-0.20	1915	0.23	1976	0.61
1930	1.46	1958	1.78	1936	1.17	1949	0.09	1903	0.15	1954	2.42	1907	2.79	1977	2.11	1989	2.61	1965	-0.28	1982	0.21	1920	0.61
1942	1.45	1930	1.77	1973	1.15	1956	-0.03	1936	0.04	1978	2.27	1998	2.77	1964	2.10	1926	2.55	1990	-0.30	1976	0.08	1929	0.57
1995	1.34	1927	1.77	1950	1.09	1912	-0.05	1895	0.00	1925	2.20	1896	2.75	1961	2.07	1940	2.50	1911	-0.32	1914	-0.07	1949	0.55
1925	1.25	1895	1.74	1964	0.88	1944	-0.14	1900	-0.03	1919	2.05	1954	2.71	1990	1.90	1969	2.42	1923	-0.38	1921	-0.11	1897	0.49
1961	1.21	1924	1.61	1941	0.87	1962	-0.29	1961	-0.04	1902	2.04	1959	2.60	1986	1.89	1995	2.30	1916	-0.41	1995	-0.19	1965	0.42
1969	1.21	1933	1.54	1918	0.87	1985	-0.30	1966	-0.13	1908	1.97	1997	2.53	1973	1.87	1914	2.13	1941	-0.44	1971	-0.20	1964	0.37

Ranked Net Rainfall

January		February		March		April		May		June		July		August		September		October		November		December	
1989	1.12	1910	1.54	1933	0.76	1907	-0.32	1958	-0.14	1981	1.97	1900	2.50	1972	1.87	1954	2.03	1912	-0.51	1936	-0.28	1979	0.35
1908	1.11	1959	1.39	1965	0.75	1966	-0.46	1930	-0.20	1941	1.95	1925	2.46	1940	1.84	1977	2.00	1927	-0.67	1908	-0.30	1909	0.35
1929	1.09	1970	1.38	1912	0.69	1983	-0.47	1972	-0.20	1927	1.89	1982	2.42	1913	1.82	1931	1.98	1895	-0.82	1959	-0.31	1959	0.30
1955	1.07	1953	1.33	1934	0.67	1989	-0.48	1916	-0.41	1933	1.76	1895	2.42	1952	1.80	1976	1.91	1943	-0.84	1985	-0.34	1921	0.28
1977	0.95	1906	1.29	1984	0.67	1924	-0.49	1909	-0.44	1983	1.70	1971	2.41	1974	1.71	1971	1.87	1960	-0.84	1981	-0.35	1922	0.23
1957	0.87	1904	1.26	1932	0.64	1984	-0.49	1901	-0.48	1916	1.66	1950	2.40	1966	1.57	1917	1.78	1982	-0.89	1979	-0.40	1919	0.11
1963	0.77	1928	1.18	1978	0.60	1961	-0.53	1931	-0.50	1946	1.61	1915	2.38	1904	1.56	1983	1.65	1933	-0.94	1897	-0.43	1948	0.07
1918	0.73	1912	1.09	1915	0.55	1916	-0.55	1938	-0.61	1907	1.58	1910	2.34	1956	1.48	1936	1.64	1957	-1.12	1910	-0.43	1981	0.06
1997	0.58	1980	1.07	1948	0.54	1919	-0.56	1942	-0.62	1899	1.55	1955	2.25	1929	1.46	1956	1.58	1989	-1.13	1957	-0.45	1912	0.05
1946	0.44	1905	1.07	1972	0.47	1905	-0.58	1952	-0.62	1938	1.54	1934	2.18	1915	1.43	1946	1.46	1997	-1.13	1958	-0.48	1931	0.02
1920	0.40	1993	1.04	1989	0.42	1996	-0.66	1974	-0.71	1957	1.40	1928	2.16	1908	1.42	1964	1.35	1985	-1.15	1952	-0.49	1915	0.01
1982	0.28	1961	0.99	1985	0.24	1914	-0.67	1956	-0.74	1944	1.40	1952	2.13	1903	1.34	1899	1.31	1896	-1.16	1949	-0.53	1936	-0.03
1934	0.25	1982	0.99	1911	0.23	1908	-0.69	1928	-0.81	1991	1.40	1923	2.08	1982	1.32	1918	1.23	1991	-1.17	1986	-0.54	1985	-0.06
1922	0.16	1994	0.98	1910	0.18	1913	-0.70	1937	-0.82	1920	1.37	1944	2.04	1897	1.25	1941	1.13	1946	-1.22	1922	-0.58	1947	-0.07
1913	0.15	1896	0.97	1896	0.18	1950	-0.71	1971	-0.87	1922	1.23	1897	2.04	1899	1.25	1966	1.09	1992	-1.28	1946	-0.58	1971	-0.08
1901	0.10	1951	0.85	1955	0.12	1940	-0.76	1964	-0.93	1990	1.23	1977	2.00	1923	1.20	1934	1.08	1948	-1.28	1989	-0.60	1955	-0.12
1938	0.09	1988	0.80	1961	0.07	1909	-0.78	1997	-0.95	1903	1.15	1920	1.98	1991	1.16	1992	1.05	1939	-1.36	1955	-0.67	1961	-0.18
1909	0.08	1975	0.78	1906	0.06	1955	-0.85	1913	-1.06	1975	1.09	1994	1.92	1919	1.12	1987	1.05	1908	-1.39	1933	-0.71	1899	-0.19
1992	0.05	1973	0.77	1927	0.05	1976	-0.92	1935	-1.14	1969	1.07	1953	1.90	1965	1.12	1943	1.04	1955	-1.41	1943	-0.72	1901	-0.19
1954	0.04	1995	0.77	1980	0.04	1904	-1.01	1988	-1.20	1963	1.07	1927	1.88	1944	1.11	1993	1.03	1970	-1.44	1973	-0.72	1896	-0.22
1944	0.02	1922	0.72	1995	-0.01	1972	-1.05	1990	-1.22	1985	1.02	1922	1.80	1955	1.11	1965	0.97	1928	-1.46	1907	-0.75	1903	-0.25
1895	0.00	1898	0.65	1997	-0.08	1923	-1.09	1993	-1.25	1960	1.00	1903	1.79	1997	1.10	1938	0.94	1954	-1.53	1938	-0.77	1954	-0.26
1919	-0.02	1925	0.56	1994	-0.11	1945	-1.10	1933	-1.25	1924	1.00	1940	1.73	1951	1.10	1955	0.90	1914	-1.54	1945	-0.78	1927	-0.31
1897	-0.05	1968	0.48	1979	-0.13	1943	-1.11	1977	-1.27	1940	0.97	1964	1.73	1976	1.04	1919	0.86	1917	-1.57	1898	-0.79	1951	-0.34
1962	-0.06	1986	0.42	1925	-0.17	1990	-1.12	1973	-1.30	1997	0.92	1985	1.68	1950	1.03	1974	0.81	1935	-1.59	1948	-0.83	1904	-0.39
1984	-0.07	1977	0.41	1909	-0.34	1964	-1.14	1962	-1.31	1937	0.91	1901	1.62	1927	1.00	1939	0.81	1966	-1.60	1990	-0.87	1917	-0.41
1985	-0.08	1954	0.41	1921	-0.34	1915	-1.16	1924	-1.32	1989	0.86	1987	1.60	1916	0.97	1970	0.67	1972	-1.62	1993	-0.88	1924	-0.41
1905	-0.10	1996	0.34	1963	-0.36	1925	-1.19	1960	-1.34	1955	0.55	1963	1.58	1946	0.96	1968	0.65	1932	-1.67	1935	-1.04	1988	-0.42
1952	-0.10	1987	0.34	1895	-0.40	1965	-1.21	1944	-1.40	1917	0.51	1908	1.46	1933	0.94	1942	0.54	1929	-1.75	1927	-1.05	1928	-0.47
1933	-0.12	1926	0.31	1992	-0.41	1901	-1.29	1926	-1.41	1897	0.51	1969	1.45	1975	0.93	1932	0.52	1926	-1.77	1961	-1.09	1960	-0.47
1965	-0.12	1991	0.31	1923	-0.51	1936	-1.30	1948	-1.42	1909	0.28	1989	1.39	1993	0.93	1952	0.48	1949	-1.78	1965	-1.09	1993	-0.54
1947	-0.16	1969	0.24	1946	-0.53	1906	-1.33	1896	-1.52	1935	0.17	1986	1.38	1989	0.86	1981	0.47	1934	-1.79	1975	-1.10	1895	-0.58
1972	-0.22	1931	0.20	1904	-0.55	1979	-1.36	1998	-1.54	1987	0.17	1917	1.34	1931	0.69	1923	0.42	1964	-1.82	1906	-1.18	1952	-0.59
1967	-0.26	1955	0.17	1914	-0.62	1998	-1.36	1917	-1.61	1971	0.07	1966	1.32	1896	0.69	1895	0.41	1913	-1.84	1913	-1.18	1939	-0.60
1956	-0.27	1979	0.13	1954	-0.66	1902	-1.37	1897	-1.67	1915	0.01	1904	1.29	1960	0.65	1916	0.40	1930	-1.84	1978	-1.22	1982	-0.63
1960	-0.27	1935	0.03	1951	-0.73	1921	-1.47	1904	-1.68	1958	-0.00	1983	1.14	1970	0.65	1904	0.26	1978	-1.94	1996	-1.23	1966	-0.66
1932	-0.30	1938	0.01	1966	-0.77	1927	-1.53	1918	-1.72	1973	-0.02	1949	1.13	1907	0.65	1984	0.09	1905	-1.95	1964	-1.23	1980	-0.66
1939	-0.34	1908	-0.04	1899	-0.79	1969	-1.54	1955	-1.75	1928	-0.06	1936	1.10	1968	0.61	1898	0.04	1967	-1.96	1939	-1.24	1937	-0.73
1937	-0.34	1997	-0.07	1938	-0.80	1988	-1.57	1981	-1.79	1977	-0.11	1931	1.08	1984	0.54	1896	-0.09	1925	-2.02	1950	-1.27	1992	-0.76
1911	-0.36	1974	-0.12	1939	-0.82	1917	-1.61	1950	-1.80	1913	-0.14	1980	0.96	1936	0.51	1980	-0.18	1931	-2.09	1970	-1.27	1923	-0.85
1916	-0.36	1956	-0.17	1971	-0.84	1974	-1.68	1902	-1.82	1918	-0.21	1914	0.95	1978	0.42	1996	-0.19	1906	-2.17	1901	-1.32	1946	-0.91
1923	-0.44	1921	-0.33	1898	-0.86	1911	-1.71	1908	-1.85	1911	-0.30	1911	0.90	1920	0.40	1967	-0.26	1973	-2.36	1909	-1.33	1970	-0.91

Appendix C

Maximum Averaged S-65E Flow (cfs-14 day) Estimated for each Month

Maximum Averaged S-65E Flow (cfs-14 day)

1930	2333	1958	1978	3030	4185	12225	12797	5869	4536	4658	4466	2865
1931	2998	3099	3629	2960	3601	1977	1555	1197	1333	1301	1151	965
1932	819	678	565	477	348	926	1018	936	2598	1859	1235	1042
1933	797	679	589	627	594	339	1145	3307	10877	6289	4272	2666
1934	1911	1573	1371	1443	1495	6441	8297	6416	4728	4113	2410	1856
1935	1379	1071	915	621	543	358	546	576	1501	3708	2655	1535
1936	1314	2504	3174	2904	1811	1814	1927	2111	2246	2424	2424	1954
1937	1686	1373	1339	1534	1258	1023	1033	985	1051	3464	4565	4157
1938	2708	1986	1601	1249	883	796	1221	1664	1418	1623	1738	1199
1939	933	758	613	447	471	398	1197	2141	3854	4316	2624	2239
1940	1667	1578	1513	1573	1388	1087	1430	1888	3006	3265	1985	1380
1941	1689	1808	1738	2044	2058	1789	3223	4137	2856	3463	3556	2561
1942	3172	3014	4163	3623	2234	3330	2789	2370	2226	2065	1577	1219
1943	1042	849	833	668	544	522	1416	1464	1836	4058	2238	1599
1944	1291	1107	872	1096	1071	599	696	1001	1265	1402	1801	1728
1945	1553	1421	1246	968	719	516	1663	4551	9245	9555	5623	3953
1946	3002	2181	1729	1521	1133	1122	938	1364	2488	2563	1911	1667
1947	1446	1161	1704	1742	1616	3810	5209	5779	10462	12240	8026	5486
1948	4401	4503	3421	2354	1971	1584	1592	1729	4711	16090	7698	4674
1949	3025	2189	1682	1133	887	622	1105	1523	5786	7829	5764	3389
1950	2119	1670	1421	1080	792	792	828	645	817	1975	2986	1223
1951	1131	1146	1061	1804	2436	1240	1734	2164	1734	4605	3457	2735
1952	2046	1654	1452	1391	1526	1727	1638	1781	2001	5339	5533	3081
1953	2129	1710	1537	1550	1561	1471	1704	2767	7446	14669	10710	7489
1954	6401	4846	3317	2471	1812	3737	3909	3009	2288	2846	2281	1911
1955	1495	1411	1154	835	668	418	1366	1416	1279	1189	744	503
1956	443	364	308	235	148	113	168	235	648	5874	6329	1756
1957	1248	1134	1528	1689	2286	2244	2576	3627	5131	4931	3449	2324
1958	2786	3231	3323	3259	2970	2353	2129	2124	1939	1654	1094	756
1959	755	821	2014	3252	2509	5782	7639	5442	6539	9666	9699	5873
1960	4008	3211	3817	6220	5586	2941	4506	10284	13919	14069	9711	5809
1961	3607	2840	2132	1813	1319	963	966	1105	1328	758	474	342
1962	253	202	148	137	100	492	1356	1755	3194	2417	681	681
1963	681	681	681	681	681	681	681	681	681	681	681	681
1964	681	681	681	681	681	681	681	681	681	2789	2195	483
1965	853	1029	2036	1583	990	510	1297	2084	2126	2161	1969	1168
1966	1018	2426	4373	3536	2306	2018	2176	3839	3066	3091	2319	338
1967	239	331	250	181	399	716	563	1944	2659	2448	1002	267
1968	286	230	214	127	274	4166	8331	5137	3277	2756	2364	434
1969	2209	1819	4906	4056	2399	2229	1299	2171	2532	13661	6564	5879
1970	6288	3284	4243	5492	1400	665	1338	1377	272	980	152	308
1971	1424	3215	1899	73	2	422	1028	818	2464	1472	952	137
1972	35	362	165	493	875	4209	4114	1143	1285	76	65	401
1973	662	2222	2139	5924	3527	1494	1453	3226	5576	3494	386	172
1974	75	1324	785	470	992	1173	11725	8744	6085	3471	269	146
1975	97	79	176	1616	2096	1874	909	2866	2133	3797	2593	180
1976	169	1689	2819	1055	2192	2668	1772	6672	4578	2102	113	2029
1977	2516	2115	2476	1291	2	70	44	37	527	606	139	884
1978	2981	3535	4408	920	1639	1642	3569	9256	2942	1094	271	756
1979	5536	3744	3322	100	2994	1449	886	1291	7089	8147	1201	1521
1980	1641	2554	3035	1559	2274	1957	368	439	685	220	118	105
1981	116	165	137	4	3	2	2	22	1568	918	25	4
1982	9	10	52	1251	2091	5809	8519	6274	2852	5683	738	508
1983	1389	8665	8034	5933	4184	416	2430	3048	2192	1839	234	2826
1984	3019	2433	3010	3716	2316	2805	2071	3428	1653	156	166	240
1985	25	40	25	0	1118	298	388	1758	2566	2038	137	118
1986	2470	2268	2063	1756	995	886	1896	2009	2305	609	430	199
1987	3788	3438	2232	4222	2871	450	378	405	459	2986	5606	6927
1988	1699	2518	4974	4811	1592	973	474	877	4310	967	20	8

Maximum Averaged S-65E Flow (cfs-14 day)

1989	818	1660	1954	2289	1904	1313	204	302	570	1169	335	117
1990	2072	2708	3206	924	336	411	1508	1206	734	2012	360	34
1991	221	115	535	1363	2808	3125	3404	6309	6412	2784	1152	147
1992	88	1912	1954	2484	2721	986	2832	4689	5396	942	383	1177
1993	5762	5439	2420	6783	3034	269	94	77	890	407	263	62
1994	97	277	1569	1711	260	3219	5632	2171	4676	6062	7340	8283
1995	3629	3285	3666	3329	1342	953	1733	7588	8210	6371	5541	2322
1996	3562	2593	1493	3321	2122	1155	1124	1623	1257	1034	207	37
1997	1043	2688	161	459	4466	1329	526	6439	2851	1672	4325	9181
1998	8564	8934	10290	9104	1315	-999	-999	-999	-999	-999	-999	-999

Appendix D

Monthly Ranked S-65E Flow (cfs-14 day)

Ranked S-65E Flows(cfs-14 day)

January		February		March		April		May		June		July		August		September		October		November		December	
1998	8564	1998	8934	1998	10290	1998	9104	1960	5586	1930	12225	1930	12797	1960	10284	1960	13919	1948	16090	1953	10710	1997	9181
1954	6401	1983	8665	1983	8034	1993	6783	1997	4466	1934	6441	1974	11725	1978	9256	1933	10877	1953	14669	1960	9711	1994	8283
1970	6288	1993	5439	1988	4974	1960	6220	1930	4185	1982	5809	1982	8519	1974	8744	1947	10462	1960	14069	1959	9699	1953	7489
1993	5762	1954	4846	1969	4906	1983	5933	1983	4184	1959	5782	1968	8331	1995	7588	1945	9245	1969	13661	1947	8026	1987	6927
1979	5536	1948	4503	1978	4408	1973	5924	1931	3601	1972	4209	1934	8297	1976	6672	1995	8210	1947	12240	1948	7698	1969	5879
1948	4401	1979	3744	1966	4373	1970	5492	1973	3527	1968	4166	1959	7639	1997	6439	1953	7446	1959	9666	1994	7340	1959	5873
1960	4008	1978	3535	1970	4243	1988	4811	1993	3034	1947	3810	1994	5632	1934	6416	1979	7089	1945	9555	1969	6564	1960	5809
1987	3788	1987	3438	1942	4163	1987	4222	1979	2994	1954	3737	1947	5209	1991	6309	1959	6539	1979	8147	1956	6329	1947	5486
1995	3629	1995	3285	1960	3817	1969	4056	1958	2970	1942	3330	1960	4506	1982	6274	1991	6412	1949	7829	1949	5764	1948	4674
1961	3607	1970	3284	1995	3666	1984	3765	1987	2871	1994	3219	1972	4114	1930	5869	1974	6085	1995	6371	1945	5623	1937	4157
1996	3562	1958	3231	1931	3629	1942	3623	1991	280[illegible]	1991	3125	1954	3909	1947	5779	1949	5786	1933	6289	1987	5606	1945	3953
1942	3172	1971	3215	1948	3421	1966	3536	1992	2721	1960	2941	1978	3569	1959	5442	1973	5576	1994	6062	1995	5541	1949	3389
1949	3025	1960	3211	1958	3323	1995	3329	1959	2509	1984	2805	1991	3404	1968	5137	1992	5396	1982	5883	1952	5533	1952	3081
1984	3019	1931	3099	1979	3322	1996	3321	1951	2436	1976	2668	1941	3223	1992	4689	1957	5131	1956	5874	1937	4565	1930	2865
1946	3002	1942	3014	1954	3317	1958	3259	1969	2399	1958	2353	1992	2832	1945	4551	1934	4728	1952	5339	1930	4466	1983	2826
1931	2998	1961	2840	1990	3206	1959	3252	1984	2316	1957	2244	1942	2789	1941	4137	1948	4711	1957	4931	1997	4325	1951	2735
1978	2981	1990	2708	1936	3174	1930	3030	1966	2306	1969	2229	1957	2576	1966	3839	1994	4676	1930	4658	1933	4272	1933	2666
1958	2786	1997	2688	1980	3035	1931	2960	1957	2286	1966	2018	1983	2430	1957	3627	1976	4578	1951	4605	1941	3556	1941	2561
1938	2708	1996	2593	1984	3010	1936	2904	1980	2274	1931	1977	1966	2176	1984	3428	1930	4536	1939	4316	1951	3457	1957	2324
1977	2516	1980	2554	1976	2819	1992	2484	1942	2234	1980	1957	1958	2129	1933	3307	1988	4310	1934	4113	1957	3449	1995	2322
1986	2470	1988	2518	1977	2476	1954	2471	1976	2192	1975	1874	1984	2071	1973	3226	1939	3854	1943	4058	1950	2986	1939	2239
1930	2333	1936	2504	1993	2420	1948	2354	1996	2122	1936	1814	1936	1927	1983	3048	1968	3277	1975	3797	1935	2655	1976	2029
1969	2209	1984	2433	1987	2232	1989	2289	1975	2096	1941	1789	1986	1896	1954	3009	1962	3194	1935	3708	1939	2624	1936	1954
1953	2129	1966	2426	1973	2139	1941	2044	1982	2091	1952	1727	1976	1772	1975	2866	1966	3066	1973	3494	1975	2593	1954	1911
1950	2119	1986	2268	1961	2132	1961	1813	1941	2058	1978	1642	1951	1734	1953	2767	1940	3006	1974	3471	1936	2424	1934	1856
1990	2072	1973	2222	1986	2063	1951	1804	1948	1971	1948	1584	1995	1733	1942	2370	1978	2942	1937	3464	1934	2410	1956	1756
1952	2046	1949	2189	1965	2036	1986	1756	1989	1904	1973	1494	1953	1704	1969	2171	1941	2856	1941	3463	1968	2364	1944	1728
1934	1911	1946	2181	1959	2014	1947	1742	1954	1812	1953	1471	1945	1663	1994	2171	1982	2852	1940	3265	1966	2319	1946	1667
1988	1699	1977	2115	1930	1978	1994	1711	1936	1811	1979	1449	1952	1638	1951	2164	1997	2851	1966	3091	1954	2281	1943	1599
1941	1689	1938	1986	1989	1954	1957	1689	1978	1639	1997	1329	1948	1592	1939	2141	1967	2659	1987	2986	1943	2238	1935	1535
1937	1686	1930	1958	1992	1954	1975	1616	1947	1616	1989	1313	1931	1555	1958	2124	1932	2598	1954	2846	1964	2195	1979	1521
1940	1667	1992	1912	1971	1899	1965	1583	1988	1592	1951	1240	1990	1508	1936	2111	1985	2566	1964	2789	1940	1985	1940	1380
1980	1641	1969	1819	1941	1738	1940	1573	1953	1561	1974	1173	1973	1453	1965	2084	1969	2532	1991	2784	1965	1969	1950	1223
1945	1553	1941	1808	1946	1729	1980	1559	1952	1526	1996	1155	1940	1430	1986	2009	1946	2488	1968	2756	1946	1911	1942	1219
1955	1495	1953	1710	1947	1704	1953	1550	1934	1495	1946	1122	1943	1416	1967	1944	1971	2464	1946	2563	1944	1801	1938	1199
1947	1446	1976	1689	1949	1682	1937	1534	1970	1400	1940	1087	1955	1366	1940	1888	1986	2305	1967	2448	1938	1738	1992	1177
1971	1424	1950	1670	1938	1601	1946	1521	1940	1388	1937	1023	1962	1356	1952	1781	1954	2288	1936	2424	1942	1577	1965	1168
1983	1389	1989	1660	1994	1569	1934	1443	1995	1342	1992	986	1970	1338	1985	1758	1936	2246	1962	2417	1932	1235	1932	1042
1935	1379	1952	1654	1953	1537	1952	1391	1961	1319	1988	973	1969	1299	1962	1755	1942	2226	1965	2161	1979	1201	1931	965
1936	1314	1940	1578	1957	1528	1991	1363	1998	1315	1961	963	1965	1297	1948	1729	1983	2192	1976	2102	1991	1152	1977	884
1944	1291	1934	1573	1940	1513	1977	1291	1937	1258	1995	953	1938	1221	1938	1664	1975	2133	1942	2065	1931	1151	1978	756
1957	1248	1945	1421	1996	1493	1982	1251	1946	1133	1932	926	1939	1197	1996	1623	1965	2126	1985	2038	1958	1094	1958	756

Ranked S-65E Flows(cfs-14 day)

January		February		March		April		May		June		July		August		September		October		November		December	
1951	1131	1955	1411	1952	1452	1938	1249	1985	1118	1986	886	1933	1145	1949	1523	1952	2001	1990	2012	1967	1002	1982	508
1997	1043	1937	1373	1950	1421	1949	1133	1944	1071	1938	796	1996	1124	1943	1464	1958	1939	1950	1975	1971	952	1955	503
1943	1042	1974	1324	1934	1371	1944	1096	1986	995	1950	792	1949	1105	1955	1416	1943	1836	1932	1859	1955	744	1964	483
1966	1018	1947	1161	1937	1339	1950	1080	1974	992	1967	716	1937	1033	1970	1377	1951	1734	1983	1839	1982	738	1968	434
1939	933	1951	1146	1945	1246	1976	1055	1965	990	1970	665	1971	1028	1946	1364	1984	1653	1997	1672	1963	474	1972	401
1965	853	1957	1134	1955	1154	1945	968	1949	887	1949	622	1932	1018	1979	1291	1981	1568	1958	1654	1986	430	1961	342
1932	819	1944	1107	1951	1061	1990	924	1938	883	1944	599	1961	966	1990	1206	1935	1501	1938	1623	1973	386	1966	338
1989	818	1935	1071	1935	915	1978	920	1972	875	1943	522	1946	938	1931	1197	1938	1418	1971	1472	1992	383	1970	308
1933	797	1965	1029	1944	872	1955	835	1950	792	1945	516	1975	909	1972	1143	1931	1333	1944	1402	1990	360	1967	267
1959	755	1943	849	1943	833	1943	668	1945	719	1965	510	1979	886	1961	1105	1961	1328	1931	1301	1989	335	1984	240
1973	662	1959	821	1974	785	1933	627	1955	668	1962	492	1950	828	1944	1001	1972	1285	1955	1189	1978	271	1986	199
1956	443	1939	758	1939	613	1935	621	1933	594	1987	450	1944	696	1937	985	1955	1279	1989	1169	1974	269	1975	180
1968	286	1933	679	1933	589	1972	493	1943	544	1971	422	1967	563	1932	936	1944	1265	1978	1094	1993	263	1973	172
1962	253	1932	678	1932	565	1932	477	1935	543	1955	418	1935	546	1988	877	1996	1257	1996	1034	1983	234	1991	147
1967	239	1956	364	1991	535	1974	470	1939	471	1983	416	1997	526	1971	818	1937	1051	1970	980	1996	207	1974	146
1991	221	1972	362	1956	308	1997	459	1967	399	1990	411	1988	474	1950	645	1993	890	1988	967	1984	166	1971	137
1976	169	1967	331	1967	250	1939	447	1932	348	1939	398	1985	388	1935	576	1950	817	1992	942	1970	152	1985	118
1981	116	1994	277	1968	214	1956	235	1990	336	1935	358	1987	378	1980	439	1990	734	1981	918	1977	139	1989	117
1994	97	1968	230	1975	176	1967	181	1968	274	1933	339	1980	368	1987	405	1980	685	1961	758	1985	137	1980	105
1975	97	1962	202	1972	165	1962	137	1994	260	1985	298	1989	204	1989	302	1956	648	1986	609	1980	118	1993	62
1992	88	1981	165	1997	161	1968	127	1956	148	1993	269	1956	168	1956	235	1989	570	1977	606	1976	113	1996	37
1974	75	1991	115	1962	148	1979	100	1962	100	1956	113	1993	94	1993	77	1977	527	1993	407	1972	65	1990	34
1972	35	1975	79	1981	137	1971	73	1981	3	1977	70	1977	44	1977	37	1987	459	1980	220	1981	25	1988	8
1985	25	1985	40	1982	52	1981	4	1971	2	1981	2	1981	2	1981	22	1970	272	1984	156	1988	20	1981	4
1982	9	1982	10	1985	25	1985	0	1977	2	1972	76	1972	76	1972	76	1972	76	1972	76	1972	76	1972	76

Appendix E

Possible Uses of Long-Range Weather outlooks in Water Resources (S. A. Changnon,Jr.)

POSSIBLE USES OF LONG-RANGE WEATHER OUTLOOKS IN WATER RESOURCES

Stanley A. Changnon, Jr. [1]

ABSTRACT: A series of world climate abberations that began in the 1970's led to considerable concern over climate and its possible changes (new trends and greater fluctuations). A part of this concern developed because the world, with ever increasing population, has become more sensitive to droughts, floods, and other extremes of weather that comprise climate. This concern led to the recognition that long-range weather outlooks, referred to as those for conditions 1 to 60 months ahead, had enormous utility in the management of water, agricultural, and energy resources. The need for such forecasts has led to intensive research of physical and statistical methods. Those methods available now produce predictions with accuracies promising utility for some water management endeavors. The greatest success so far has come from the statistically based methods. This has been possible because of relatively long climatic records and large computers able to handle large volumes of data and complex statistical analyses. Major areas of application of climate outlooks in water resources include: 1) operations of water management systems (river basins, reservoirs, urban water treatment systems, groundwater recharge, etc.); 2) scheduling of water supply activities (irrigation, structural renovations, etc.); and 3) anticipation of extremes. The needs for predictions range from weeks to years ahead. For example, various reservoir operations can be benefitted by 2-week rain predictions and others by predictions of rain trends over the next 2 years. Predictions correct to the nearest 6 cm are needed in scheduling reservoir releases, but instream flow needs require only a prediction of the relative future normalcy (above, near, or below normal). This paper addresses the potential applications in water resources of outlooks.

(KEY TERMS: climates; weather patterns; forecasting; long-term planning.)

INTRODUCTION

Water and climate are pervasive conditions affecting life processes and most human activities. Water supplies are sensitive to most climate variations, be they associated with man's activities or just with natural fluctuations. Central to this complex climate-water interaction issue is the prediction of the future state of the weather for weeks, seasons, and many years ahead. It appears obvious that such "climate outlooks" can be useful in a myriad of water resource activities. The general areas of application of climate predictions in water resources include: 1) operations of water management systems, 2) scheduling of water supply activities, 3) anticipation of extremes, and 4) planning of major facilities.

This paper is not a result of a long-term study; rather it attempts to review and identify the potential needs and applications of climate predictions to water issues. In a qualitative sense, I also attempted to address the future periods for which predictions are desired, and the general level of predictive accuracy believed useful. As a summary, this review identifies the major problems surrounding the use of climate predictions in water resources, and concludes with some areas of needed research.

NEEDS AND APPLICATIONS OF CLIMATE OUTLOOKS

The application of long-range precipitation outlooks in water resources may seem obvious and the major problem is building an all-inclusive list of uses. These applications embrace two major areas: water quantity, and water quality. Water resource applications, as will be shown, span a wide variety of time scales (from weeks up to 25 years), and span a wide variety of space scales ranging from a square kilometer to the continental scales.

The recognized applications of long-range precipitation outlooks, those defined as being for periods for two weeks up to 25 years, appear in Table 1. There are a large number of operational applications. Probably the most benefit from predictions would come from operating systems involving multiple uses (recreation, irrigation, floods, and water supply). Balancing multiple water requirements using a system approach that includes seasonal climatic differences in precipitation (snow melt, dry periods, or floods) would be very beneficial. Another area of high utility concerns urban runoff management with its conflicting problems of rapid drainage of heavy rainfall, while simultaneously addressing national regulations to maintain quality of drainage waters which requires treatment before release of flood waters.

[1] Chief, Illinois State Water Survey, Box 5050, Station A, Champaign, Illinois 61820.

TABLE 1. Areas of Application of Climate Predictions (2 Weeks to 25 Years) in Water Resources.

A. Operations of water management systems
   1. River basins (multiple control locales)
      a. Snow melt (amount and time) = water supply and flood potential
      b. Water quality – water supply and urban and rural wastes, dilution capacity, and repelling salinity
      c. Transportation adjustments
      d. Hydroelectric power generation
      e. Stormwater management (use of flood control space)
      f. Ice formation and breakup
      g. Irrigation
      h. Recreation
      i. Multiple uses – balancing complex needs
   2. Individual reservoirs
      a. Single or multiple-purpose reservoir operations
      b. Maintain instream flow needs
      c. Short vs long range management options
   3. Urban water treatment systems
      a. Storage and treatment scheduling
      b. Street cleaning
   4. Interbasin transfers or releases
   5. Recharge of groundwater aquifers
   6. Combined groundwater-surface water supply systems
   7. Addressing regulations and their enforcements
   8. Natural lakes
      a. Ice formation and breakup
      b. Navigation
      c. Recreation
      d. Regulation

B. Scheduling water supply activities
   1. Long-term data collection and scientific investigations (streamflow, sediment transport, etc.)
   2. Irrigation
   3. Planned weather modification use and operations
   4. Structural renovations and/or construction
      a. Dams and channel repair
      b. Silt removal, eutrophication modification
      c. Levees
      d. Installation of best management practices
      e. Maintenance of urban quality and supply systems
   5. Farming in bottomlands

C. Anticipation of extremes
   1. Begin and end of wet periods
   2. Begin and end of droughts

D. Planning of major facilities
   1. Design of waste treatment and storm water facilities
   2. Structures to halt or alter river courses
   3. Development of water supply sources
   4. Prediction of sustained yield of aquifers

The scheduling of water supply activities, and particularly means of applying extra water (irrigation and weather modification), certainly would benefit from use of long-term outlooks. The anticipation of extremes is essentially a cross-cutting issue that affects operational scheduling and a host of other water activities. Anticipation of the beginning and ending of droughts, or wet periods, as well as their general magnitude, would be of enormous value.

The final general area of application is identified as planning of major facilities with multi-year life times. Obviously the types of predictions desired are for quite long-term, 10 to 25-year future conditions. In general, past planning input has tended to be either the period of record or normal 30-year precipitation.

A few examples of climate prediction applications are in order. A 2-week precipitation forecast is of great value in reservoir operation for flood control. It could be used to lower the water level of the reservoir to absorb about 1/2 of the expected inflow from a storm, assuming 50 percent accuracy of the predicted rainfall amount. Flow releases can be moderate and extended over a 2-week period. The prediction period duration will depend on the size of the reservoir; a week for a small reservoir; up to a month for a large reservoir.

Longer-term predictions are needed for operating reservoirs to meet instream flow needs. Low flows downstream can be increased by reducing high flow releases for above average inflows if precipitation predictions are available for one to six months in advance and if they indicate below average precipitation. The reliability of the predictions can be useful even if reliability decreases within increasing time. Knowledge of both shorter term (2 to 4 weeks) and the longer term predictions can be utilized in reservoir operations to maximize the overall benefits.

In summary, these illustrations and the applications listed in Table 1 point to the wide potential utility of long-range climate predictions. They vary graphically and they vary seasonally, and they vary from lead time needed as well as the period being predicted. Also, the level of accuracy varies according to the applications. The following sections address these issues.

PREDICTIVE PERIODS

In addressing the temporal aspects of long-term climate outlooks, it is important to recognize and separate the lead time vs the period of predictions. The periods covered by outlooks are those weeks, months, seasons, or years for which the prediction is made. The lead time refers to the period of time before the outlook period begins. Major emphases here is on the relationship between the applications of precipitation predictions and periods of predictions. It is recognized that lead times, those prior to the predicted period, differ to satisfy various design and scheduling operations. Outlooks for future periods of 1 up to 12 months in length would be very helpful in water supply forecasting. It is not so important to hit the right day or week of a storm, but to predict a monthly value that is reasonably close. Predictions of the general magnitude of precipitation for one or two years in the future would have a great impact on the manner in which reservoirs storing water for irrigation are operated in California (McCullough, 1981).

Table 2 presents periods of predictions, for various selected applications of predictions. These are sorted into five classes and the same applications appear under more than one period. Reservoir operations benefit by predictions for 2- to 4-week periods (such as for flood control information); also for periods of 2- to 6-month periods in the future (reservoir operations for maintaining suitable downstream flows), and also for 1- to 2-year future periods (yield management of single-purpose reservoirs in times of drought). A primary finding revealed in Table 2 is that there are needs for predictions of precipitation for a variety of periods, but most occur between 2 weeks and 10 years.

DESIRED PREDICTIVE ACCURACIES

Not much is known about the level of accuracy of precipitation predictions needed to satisfy water resource applications. Since their use has been limited, little thought has been given to this issue. McCullough (1981) indicates that 3-class (terciles) predictions (wet, near normal, and dry) have value. Most hydrologists have indicated, in thinking about precipitation predictions, that they want them "converted" to actual runoff quantities which assumes a capability for predicting a specific precipitation value.

Several research hydrologists were asked to consider some of the major applications (Table 1) and to answer the question of whether precipitation amounts in terciles, or with a specific value being correct to ± 6 to 9 cm, were useful. Results are shown in Table 3. Certain reservoir operations of a longer term nature can be satisfied by precipitation predictions in the 3-class levels, whereas others of the shorter term nature need specific outlooks with error bars of a few centimeters. Many of the applications of the long-range predictions could be satisfied with the 3-class system.

PROBLEMS

This review of long-term precipitation outlooks and their potential applications to water resources reveals a considerable number of applications. Research to develop precipitation outlooks has been emphasized in recent years, and some moderate accuracy exists. A recent meeting (May 1981) of water resource experts and the NWS staff who issue climate predictions revealed that there is a general lack of awareness of the current level of accuracy, and certain major problems exist in the area of utility and development of the precipitation predictions (CAC, 1981).

TABLE 2. Periods Covered by Predictions Desired for Various Applications.

2 to 4 Week Periods	2 to 6 Month Periods	1 to 2 Year Periods	5 to 10 Year Periods	10 to 25 Year Periods
Reservoir operation	Reservoir operation	Reservoir operation	Water supply source develop	Water supply source develop
Reservoir release rates	Instream flow needs	Crop variety selection	Sustained yield from aquifers	
Irrigation requirements	Navigation	Water supply from existing source	Power generation	
Waste treatment plant loadings	Floodplain farming	Plan for stream flow and sediment data collection	Design of waste treatment plants	
Storm water management	Water supply from existing source	Flood mitigation plans	New storm water facilities	
Water quality variation	Storm water management	Construction of new levees	Planning to halt stream course changes	
Flood emergency plans	Water quality variation	Crop variety plantings		
City street cleaning and sweeping	Maintenance of levees	Planning to prevent the deterioration of quality BMP installation		
Water system repairs construction	Snow removal and clearing plans			
	Effects on water quality			
	Hydroelectric scheduling			
	Recreation usage of rivers and reservoir levels			

TABLE 3. General Level of Accuracy Desired in Climate (Seasonal and Annual) Predictions of Precipitation.

Specific Value with Accuracy Limits of 3 to 6 cm	Precipitation Predicted Within Above, Near or Below Normal Terciles
Reservoir operation (short period)	Reservior operation (long period)
Reservoir release rates	Instream flow needs Water supply
Flood emergencies	Navigation Stream flow and sediment Data collection Floods and flood mitigation
Storm water management	Snow removal Crop variety selection Levee construction and maintenance
Irrigation	New storm water facilities BMP applications, aquifer yield, power generation Stream course changes Water quality

A major problem, when one reviews the situation, is a lack of awareness by the atmospheric scientists of the specific needs of hydrologists, and in turn, a lack of awareness of the hydrologists about the emerging capabilities of long-range predictions. Interactions should help in improving the awareness needed by both groups.

Utility of the outlooks by hydrologists depends on their perceptions about the credibility of the predictions. Long-range outlooks represent an area of emerging capabilities and part of the credibility problem relates to the fact that many hydrologists are not aware of how outlooks are calculated. Again, an informational-educational effort is needed.

An important problem with most existing outlooks of precipitation is the lack of expression of the uncertainty levels or error ranges around the predicted value. Most hydrologists have engineering backggrounds and are able to deal with the statistical uncertainty. Hence, expressions of precipitation predictions as probabilities can be understood by hydrologists.

Another problem relating to long-term precipitation predictions relates to the size of area being predicted for. Applications desired by hydrologists can vary widely, from very small basins to very large basins. These may or may not match skills available in precipitation predictions. Some seasonal precipitation predictions are 60 percent accurate for large areas but are no better than chance for small areas. Hence most long-term precipitation predictions relate to very large sized areas and represent regional means.

Another problem area relates to concepts of how to mix or combine long-range outlooks with short-range (hours to days) weather forecasts. Anyone can be confused by their differences, and this interrelationship needs to be studied and explained better by atmospheric scientists. A seasonal forecast for near normal rainfall can have wet periods lasting several days.

Another problem relates to the lead times currently used in most long-range predictions. Many water resource applications have lead time requirements greater than currently used. Water resource experts believe that to be most useful, seasonal predictions of precipitation should be updated monthly and issued with 9-month lead times, as opposed to issuance on the first day of the season.

SOME RESEARCH NEEDS

The above problems point to certain research needs beyond a need to have more accurate predictions. Some research needed relates to studies of how long-range predictions are expressed. The probabilities in space and time, of the predicted magnitude of precipitation need to be defined and expressed in predictions. Secondly, prediction possibilities for weather extremes and the general variability need to be studied. Predictive research also needs to address the occurrences of persistent homogenous (prolonged wet or dry) periods.

It is apparent from these problems, and the research needs, that a major effort of education and interaction is needed between hydrologists and atmospheric scientists. This will help optimize the research and alert each group of the needs and capabilities of each group.

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Appendix F

Using NOAA's New Climate Outlooks In Operational Hydrology

Thomas E. Croley II

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USING NOAA'S NEW CLIMATE OUTLOOKS IN OPERATIONAL HYDROLOGY

By Thomas E. Croley II[1]

ABSTRACT: The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center recently began issuing new multiple long-lead outlooks of meteorological probabilities. Operational hydrology approaches for generating probabilistic hydrological outlooks must be compatible with these meteorological outlooks yet preserve spatial and temporal relationships observed in past meteorology. Many approaches, however, either limit the use of historical data to be compatible with meteorological outlooks or limit compatibility with the outlooks to allow fuller use of historical data. An operational hydrology approach that uses all historical data while remaining compatible with many of the new long-lead outlooks, in order of user priority, is described here. The approach builds a hypothetical very large structured set of possible future scenarios, to be treated as a "sample" from which to estimate outlook probabilities and other parameters. The use of this hypothetical set corresponds to the weighted use of a scenario set based on historical data. The determination of weights becomes an optimization problem for the general case. An example illustrates the concepts and method.

MAKING PROBABILISTIC OUTLOOKS

Meteorological Probability Outlooks

Advances in long-range forecasting techniques recently enabled useable climate predictions beyond the previous 90-day limit. The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center now provides each month a "Climate Outlook," consisting of a one-month outlook for the next month and 13 three-month outlooks, going into the future in overlapping fashion in one-month steps. Background and recent history on seasonal forecasting are provided elsewhere (Barnston et al. 1994; van den Dool 1994; Livezey 1990; Wagner 1989; Epstein 1988; Ropelewski and Halpert 1986; Gilman 1985).

The forecasts in the "Climate Outlook" are formed by a combination of methods. For U.S. air temperature and precipitation forecasts, these methods include: (1) Canonical correlation analysis (Barnston and Ropelewski 1992) relating spatial anomalies of sea surface temperature, Northern Hemisphere 700 mb height, and the U.S. surface climate; (2) use of observed interannual persistence of anomalies (Huang et al. 1994); and (3) forecasts from six-month general circulation models driven by sea surface temperatures [a set persisted from one half-month earlier and a set assembled from coupled ocean-atmosphere model runs (Ji et al. 1994)]. The general circulation model is a version of the National Meteorological Center medium range forecast model with special developmental emphasis on tropical processes.

Each outlook estimates probabilities of average air temperature and total precipitation falling within preselected value ranges. The value ranges (low, normal, and high) are defined as the lower, middle, and upper thirds of observations over the period 1961–90 for each variable. The climate outlooks presume that one of only four possibilities exist for the probabilities for each variable: (1) The probability of being in the high range exceeds one-third and the probability of being in the low range is reduced accordingly (it remains at one-third for the normal range), referred to as being "above normal"; (2) the probability of being in the normal range exceeds one-third and the probabilities of being in the low and high ranges are reduced accordingly and are equal, referred to as being "normal"; (3) the probability of being in the low range exceeds one-third and the probability of being in the high range is reduced accordingly (it remains at one-third for the normal range), referred to as being "below normal"; or (4) skill is insufficient to make a forecast and so probabilities of one-third in each range are used, referred to as "climatological."

Hydrological Probability Outlooks

Users of these climate outlooks can interpret the forecast probabilities in terms of the impacts on themselves through "operational hydrology" approaches. Possibilities for the future are identified, which resemble past meteorology (preserving observed spatial and temporal relationships) yet are compatible with the climate outlooks. Some operational hydrology approaches consider historical meteorology as possibilities for the future by segmenting the historical record and using each segment with models to simulate a hydrological possibility for the future. Each segment of the historical record then has associated time series of meteorological and hydrological variables, representing a possible "scenario" for the future. The approach can then consider the resulting set of possible future scenarios as a statistical sample and infer probabilities and other parameters associated with both meteorology and hydrology through statistical estimation from this sample (Croley 1993; Croley and Lee 1993; Croley and Hartmann 1990; Day 1985; Smith et al. 1992). Other operational hydrology approaches use time series models of the historical data to generate the "sample." This increases the precision of the resulting statistical estimates, since large samples can be generated, but not the accuracy. Use of the historical record to directly build a sample for statistical estimation avoids the loss of representation consequent with the use of time series models, but requires a sufficiently large historical record.

The operational hydrology approach uses statistical sampling tools as if the set of possible future scenarios were a single "random sample" (i.e., the scenarios are independent of each other and equally likely). This means that the relative frequencies of selected events are fixed at values different (generally) from those specified in climate outlooks. Only by restructuring the set of possible future scenarios can we obtain relative frequencies of selected events that match climate outlooks. This restructuring violates the assumption of independent and equally likely scenarios (no random sample) from the point of view of the historical record (a priori information). However, the restructured set can be viewed as a random sample ("posterior" information) of scenarios conditioned on climate outlooks. There are many methods for restructuring the

[1]Res. Hydro., Great Lakes Envir. Res. Lab., 2205 Commonwealth Blvd., Ann Arbor, MI 48105-1593.

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set of possible future scenarios (Croley 1993; Day 1985; Ingram et al. 1995; Smith et al. 1992).

BUILDING A STRUCTURED SET

In building an operational hydrology set of possible future scenarios from which to estimate probabilities and other parameters associated with various meteorological and hydrological variables, consider constructing a structured set that, when treated as a statistical sample, guarantees that probability estimates for certain variables match a priori settings. That is, we can build a structured set of possible scenarios that gives relative frequencies of average air temperature and total precipitation (over various times in the scenarios) satisfying the a priori settings of the climate outlooks. We can arbitrarily construct a very large structured set of size N by adding (duplicating) each of the available scenarios (in the original set of n possible future scenarios); each scenario numbered i ($i = 1, \ldots, n$) is duplicated r_i times. By judiciously choosing these duplication numbers ($r_1, r_2, \ldots, r_n$), it is possible to force the relative frequency of any arbitrarily defined group of scenarios in the structured set to any desired value. For example, suppose only five of 50 (10%) 12-month scenarios beginning in June have an average June air temperature exceeding 30°C, and our a priori setting (from a climate outlook) for this exceedance is 20%. We could repeat each of these five scenarios nine times and repeat the other 45 scenarios four times to build a structured set. This structured set of size 225 ($= 5 \times 9 + 45 \times 4$) would then have a relative frequency of 20% of average June air temperature exceeding 30°C ($5 \times 9)/225 = 0.2$). For sufficiently large N, we can approximate a priori settings at any precision by using integer-valued duplication numbers, r_i. In addition

$$\sum_{i=1}^{n} r_i = N \tag{1}$$

The building of a structured set in this manner to match a priori settings is one of many arbitrary possibilities, but is suggested by considerations of constraints on estimated probability distributions for a single variable; see Appendix I.

By treating the N scenarios in the very large structured set as a statistical sample, we can estimate probabilities and calculate other parameters for all variables. In particular, consider any variable X (either historical meteorological or simulated hydrological); e.g., X might be July-August-September total precipitation, end-of-August soil moisture storage, water surface temperature on day 55, or average June air temperature. We denote the event that a variable X is less than or equal to a value x as $\{X \le x\}$ and the probability of this event as $P[X \le x]$. This probability is estimated, when considering the very large structured set as a statistical sample, by the "relative frequency" of the event in the structured set. The relative frequency of event $\{X \le x\}$ is just the number of scenarios in which the event occurs divided by the set size N

$$\hat{P}[X \le x] = \sum_{k \in \Omega} \frac{1}{N}, \quad \Omega = \{k | x_k^N \le x\} \tag{2}$$

where $\hat{P}[\;]$ = a probability estimate; and x_k^N = value of variable X for the kth scenario in the very large structured set of N scenarios. [Read the set notation in (2) as "Ω is all values of k such that $x_k^N \le x$."] Actually, there are only n different values of X (x_i^n, $i = 1, \ldots, n$) since these n values were duplicated, each by a number r_i, to create N values in the very large structured set. We can rewrite (2) in terms of the original set of possible future scenarios, for any variable X

$$\hat{P}[X \le x] = \sum_{i \in \Omega} \frac{r_i}{N}, \quad \Omega = \{i | x_i^n \le x\} \tag{3}$$

Furthermore, we can write other [illegible] the large structured set of scenarios as if it was a statistical sample) in terms of the original set. Consider the γ-probability quantile for variable X, ξ_γ; it is defined by

$$P[X \le \xi_\gamma] = \gamma \tag{4}$$

The γ-probability quantile, ξ_γ, is estimated when considering the structured set as a statistical sample, by the mth order statistic, y_m^N, where $m = \gamma N$. Order all values of X in the very large structured set (x_k^N, $k = 1, \ldots, N$) from smallest to largest to define the order statistics (y_m^N, $m = 1, \ldots, N$). The probability estimate is then

$$\hat{P}[X \le y_m^N] = \frac{m}{N}, \quad m = 1, \ldots, N \tag{5}$$

where $y_m^N = x_{k(m)}^N$; and $k(m)$ = number of the value in the structured set corresponding to the mth order. [For example, if the third value in the structured set, x_3^N, was the largest ($y_N^N = x_3^N$), then $k(N) = 3$]. Alternatively, (5) can be written as follows:

$$\hat{P}[X \le x_{k(m)}^N] = \sum_{k=1}^{m} \frac{1}{N}, \quad m = 1, \ldots, N \tag{6}$$

In terms of order statistics for the original set (y_j^n, $j = 1, \ldots, n$), there are $r_{K(j)}$ identical values of y_j^n in the very large structured set where $i(j)$ is defined similarly to $k(m)$ but for the original set in which $j = 1, \ldots, n$ and $y_j^n = x_{K(j)}^n$. Eqs. (5) and (6) may be rewritten in terms of the original set of possible future scenarios (for any variable X)

$$\hat{P}[X \le y_j^n] = \hat{P}[X \le x_{K(j)}^n] = \sum_{l=1}^{j} \frac{r_{K(l)}}{N}, \quad j = 1, \ldots, n \tag{7}$$

Likewise, the sample mean and variance of variable X over the structured set $\bar{x}$ and S^2, respectively, become, in terms of the original set

$$\bar{x} = \frac{1}{N} \sum_{k=1}^{N} x_k^N = \frac{1}{N} \sum_{i=1}^{n} r_i x_i^n \tag{8a}$$

$$S^2 = \frac{1}{N} \sum_{k=1}^{N} (x_k^N - \bar{x})^2 = \frac{1}{N} \sum_{i=1}^{n} r_i (x_i^n - \bar{x})^2 \tag{8b}$$

Rewriting (3), (7), and (8)

$$\hat{P}[X \le x] = \frac{1}{n} \sum_{i \in \Omega} w_i, \quad \Omega = \{i | x_i^n \le x\} \tag{9a}$$

$$\hat{P}[X \le y_j^n] = \frac{1}{n} \sum_{l=1}^{j} w_{K(l)}, \quad j = 1, \ldots, n \tag{9b}$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} w_i x_i^n; \quad S^2 = \frac{1}{n} \sum_{i=1}^{n} w_i (x_i^n - \bar{x})^2 \tag{9c,d}$$

where

$$w_i = \frac{n}{N} r_i \tag{10}$$

Note that

$$\sum_{i=1}^{n} w_i = n \tag{11}$$

and if all $w_i = 1$, then (9) gives contemporary (unstructured) estimates from the original set, treated as a statistical sample. Other statistics can be similarly derived.

Eq. (9a) is functionally the same as that presented by Smith et al. (1992); here, the full development of statistic weights, including resampling and empirical distribution material, is

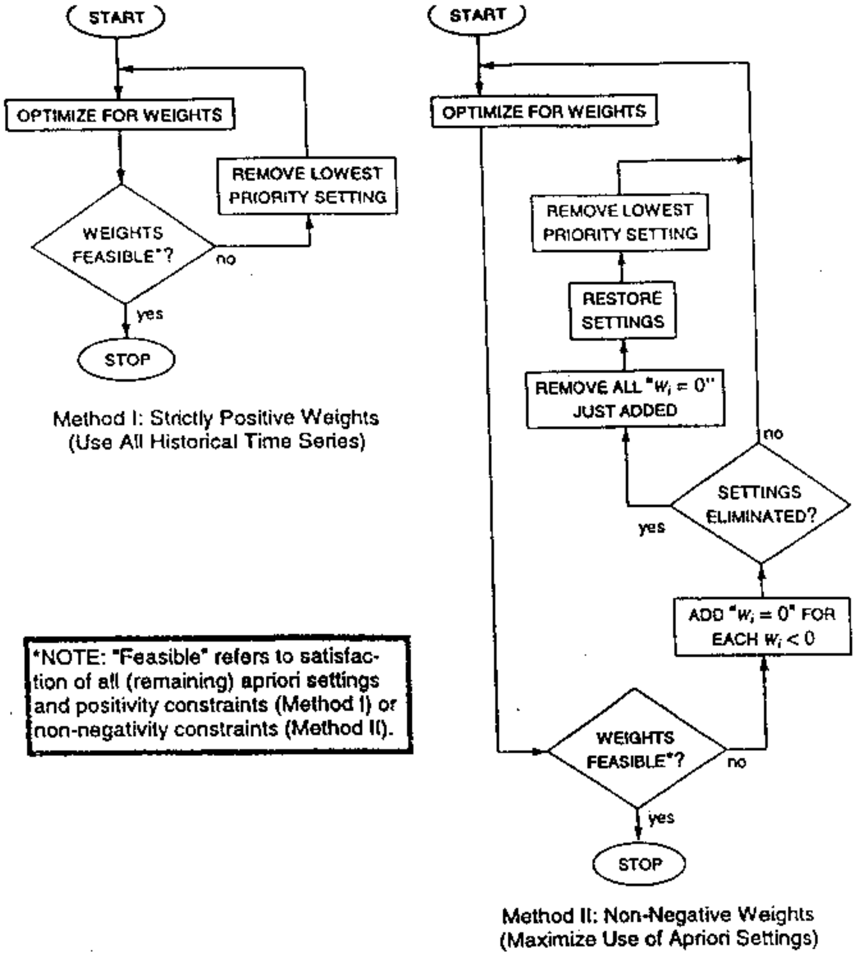

FIG. 1. Procedural Algorithms for Determining Physically Relevant Weights

TABLE 1. Meteorological Quantiles on Lake Superior Basin* for Selected Periods

Period, g (1)	Temperature Quantiles $\tau_{g,0.333}$ (°C) (2)	$\tau_{g,0.667}$ (°C) (3)	Precipitation Quantiles $\theta_{g,0.333}$ (mm) (4)	$\theta_{g,0.667}$ (mm) (5)
Jun	13.38	14.43	69	106
JJA	15.18	16.29	242	295
JAS	14.49	15.12	240	299
ASO	10.32	11.18	253	282
SON	4.08	5.02	206	247
OND	−3.40	−2.09	178	216
NDJ	−10.30	−9.27	157	190
DJF	−14.19	−12.71	135	151
JFM	−12.68	−10.75	121	135
FMA	−6.86	−4.52	123	146
MAM	0.88	2.13	154	177
AMJ	8.03	8.55	197	230
MJJ	13.04	13.51	234	267

*Estimated from 1961–90 daily data over the Lake Superior Basin from 230 meteorological stations Thiessen averaged spatially (Croley and Hartmann 1985).

presented and extended for other statistics. Smith et al. used climatic indices from long-range forecasts to set their weights subjectively. Here, we will set the weights objectively to match a priori climate outlook probability settings. Appendix I contains an example for matching a single set of a priori settings of probabilities by finding appropriate values of the weights, w_i. A more general approach for matching multiple settings follows.

CONSIDERING MULTIPLE OUTLOOKS

Now consider the case of multiple a priori settings (from a climate outlook) with which to match relative frequencies. For example, consider the settings from the new NOAA Climate Prediction Center "Climate Outlook"

$$\hat{P}[T_g > \tau_{g,0.667}] = a_g, \quad g = 1, \ldots, 14 \tag{12a}$$

$$\hat{P}[T_g \le \tau_{g,0.333}] = b_g, \quad g = 1, \ldots, 14 \tag{12b}$$

$$\hat{P}[\tau_{g,0.333} < T_g \le \tau_{g,0.667}] = 1 - a_g - b_g, \quad g = 1, \ldots, 14 \tag{12c}$$

$$\hat{P}[Q_g > \theta_{g,0.667}] = c_g, \quad g = 1, \ldots, 14 \tag{12d}$$

$$\hat{P}[Q_g \le \theta_{g,0.333}] = d_g, \quad g = 1, \ldots, 14 \tag{12e}$$

$$\hat{P}[\theta_{g,0.333} < Q_g \le \theta_{g,0.667}] = 1 - c_g - d_g, \quad g = 1, \ldots, 14 \tag{12f}$$

where T_g and Q_g = average air temperature and total precipitation, respectively, over period g ($g = 1$ corresponds to a one-month period, and $g = 2, \ldots, 14$ corresponds to 13 successive overlapping three-month periods); $\tau_{g,\gamma}$ and $\theta_{g,\gamma}$ = temperature and precipitation reference γ-probability quantiles for period g, respectively; and (a_g, b_g, c_g, and d_g, $g = 1, \ldots, 14$) = outlook settings. By definition, the reference γ-probability quantiles are estimated from the 1961–90 historical record for each period g. To illustrate (12), consider the June 1995 "Climate Outlook"; there is a one-month June outlook ($g = 1$ or "Jun") and 13 three-month outlooks successively lagged by one month each ($g = 2$ or "June-July-August" or "JJA," and g

Period, g	P_T[a]	P_Q[a]	Temperature Probabilities[b]			Precipitation Probabilities		
			$(-\infty, \tau_{g,0.333}]$	$(\tau_{g,0.333}, \tau_{g,0.667}]$	$(\tau_{g,0.667}, \infty)$	$(-\infty, \theta_{g,0.333}]$	$(\theta_{g,0.333}, \theta_{g,0.667}]$	$(\theta_{g,0.667}, \infty)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Jun '95	0 c	0 c	33	33	33	33	33	33
JJA '95	0 c	0 c	33	33	33	33	33	33
JAS '95	2 n	0 c	32	35	32	33	33	33
ASO '95	0 c	0 c	33	33	33	33	33	33
SON '95	3 b	0 c	36	33	30	33	33	33
OND '95	0 c	0 c	33	33	33	33	33	33
NDJ '95	0 c	0 c	33	33	33	33	33	33
DJF '95	1 a	0 c	32	33	34	33	33	33
JFM '96	2 a	10 b	31	33	35	43	33	23
FMA '96	4 a	0 c	32	33	37	33	33	33
MAM '96	3 a	0 c	30	33	36	33	33	33
AMJ '96	0 c	0 c	33	33	33	33	33	33
MJJ '96	0 c	0 c	33	33	33	33	33	33
JJA '96	0 c	0 c	33	33	33	33	33	33

[a]Probability (P_T and P_Q designate temperature and precipitation probabilities, respectively) in excess of 33% in low interval (below normal), in mid interval (normal), or in high interval (above normal); "no forecast" is indicated by "0 c" (climatological).

[b]Probabilities over the Climate Prediction Center's corresponding interval definitions. Probabilities expressed as percentages do not appear to sum to unity because of the two-digit round-off used here.

FIG. 2. NOAA Climate Prediction Center June 1995 Climate Outlook Probabilities for Lake Superior Basin

= 3, 4, . . . , 14 or "JAS," "ASO," . . . , "JJA," respectively). Eqs. (12c) and (12f) are redundant with the rest of (12) because relative frequencies sum to unity

$$\hat{P}[T_g \le \tau_{g,0.333}] + \hat{P}[\tau_{g,0.333} < T_g \le \tau_{g,0.667}]$$

$$+ \hat{P}[T_g > \tau_{g,0.667}] = 1, \; g = 1, \ldots, 14 \quad (13a)$$

$$\hat{P}[Q_g \le \theta_{g,0.333}] + \hat{P}[\theta_{g,0.333} < Q_g \le \theta_{g,0.667}]$$

$$+ \hat{P}[Q_g > \theta_{g,0.667}] = 1, \; g = 1, \ldots, 14 \quad (13b)$$

Therefore, there are four independent settings in (12) for each of the 14 climate outlooks for a total of 56, if all outlooks are used.

Rewriting (12) and (13) in light of (9a)

$$\sum_{i \in A_g} w_i = a_g n, \; A_g \equiv \{i | t_{g,i} > \tau_{g,0.667}\}, \; g = 1, \ldots, 14 \quad (14a)$$

$$\sum_{i \in B_g} w_i = b_g n, \; B_g \equiv \{i | t_{g,i} \le \tau_{g,0.333}\}, \; g = 1, \ldots, 14 \quad (14b)$$

$$\sum_{i \in C_g} w_i = c_g n, \; C_g \equiv \{i | q_{g,i} > \theta_{g,0.667}\}, \; g = 1, \ldots, 14 \quad (14c)$$

$$\sum_{i \in D_g} w_i = d_g n, \; D_g \equiv \{i | q_{g,i} \le \theta_{g,0.333}\}, \; g = 1, \ldots, 14 \quad (14d)$$

$$\sum_{i=1}^{n} w_i = n \quad (14e)$$

where $t_{g,i}$ and $q_{g,i}$ = average air temperature and total precipitation, respectively, over period g of scenario i. Alternatively, (14) can be written as follows:

$$\sum_{i=1}^{n} a_{k,i} w_i = e_k, \quad k = 1, \ldots, 57 \quad (15)$$

where $a_{k,i}$ = 0 or 1 corresponding to the exclusion or inclusion, respectively, of each variable in the foregoing sets; and e_k = climate outlook relative frequency settings specified in (12) times the number of available scenarios

$$e_k = a_k n, \quad k = 1, \ldots, 14 \quad (16a)$$

$$e_k = b_{k-14} n, \quad k = 15, \ldots, 28 \quad (16b)$$

$$e_k = c_{k-28} n, \quad k = 29, \ldots, 42 \quad (16c)$$

$$e_k = d_{k-42} n, \quad k = 43, \ldots, 56 \quad (16d)$$

$$e_k = n, \quad k = 57 \quad (16e)$$

Ordinarily, all of the Climate Prediction Center climate outlooks may not be used, in which case simply write (15) as

Period, g[a]	k[b]	Interval[c]	Inclusion in interval, $a_{k,i}$, $i = 1, \ldots, 45$[d]	e_k[d]
(1)	(2)	(3)	(4)	(5)
JAS '95	2	$(\tau_{k,0.667}, \infty)$	110011010001110100100110010000000001000111010	0.32×45
JAS '95	3	$(-\infty, \tau_{k,0.333}]$	001100101000001001010001101001010010010000001	0.32×45
SON '95	4	$(\tau_{k,0.667}, \infty)$	100001101010111100001011010001000001100000000	0.30×45
SON '95	5	$(-\infty, \tau_{k,0.333}]$	0001000000001000001100000101010011000011001010	0.36×45
DJF '95	6	$(\tau_{k,0.667}, \infty)$	100111110101100101001000001000011010001101111	0.34×45
DJF '95	7	$(-\infty, \tau_{k,0.333}]$	000000001010011010100001010011100100000000000	0.32×45
JFM '96	8	$(\tau_{k,0.667}, \infty)$	000111000100100100000000100010001011111001111	0.35×45
JFM '96	9	$(-\infty, \tau_{k,0.333}]$	010000000010001010000101010001100100000000000	0.31×45
JFM '96	10	$(\theta_{k,0.667}, \infty)$	11101110000000000111000110011101000000000110000	0.23×45
JFM '96	11	$(-\infty, \theta_{k,0.333}]$	0000000111111010000101000000001000011011000111	0.43×45
FMA '96	12	$(\tau_{k,0.667}, \infty)$	000101000100100000000000100010001011111001111	0.34×45
FMA '96	13	$(-\infty, \tau_{k,0.333}]$	010000000000000101001010100011000000000010000	0.32×45
MAM '96	14	$(\tau_{k,0.667}, \infty)$	001010100100010000010000100010001000111101111	0.36×45
MAM '96	15	$(-\infty, \tau_{k,0.333}]$	010001010001000010100111010000100000000010000	0.30×45
Entire	1	$(-\infty, \infty)$	111111111111111111111111111111111111111111111	1.00×45

[a]Period as selected (highlighted) in Figure 2.

[b]Period renumbered by priority (1 ≡ highest) as in (17).

[c]Interval as defined in Table 1.

[d]Coefficients in (17) defined for each selected period, k, of the climate outlook, and for each scenario, i, in the historical record.

FIG. 3. Boundary Condition Eq. (17) for June 1995 Outlook on Lake Superior

$$\sum_{i=1}^{n} a_{k,i} w_i = e_k, \quad k = 1, \ldots, m \tag{17}$$

where $m \le 57$, and the appropriate equations, corresponding to the unused outlooks, are omitted. We must solve the equations in (17) simultaneously to find the weights.

Generally, $m \ne n$ and some of the equations may be either redundant or nonintersecting with the rest and must be eliminated. (If $m > n$, then $m - n$ of the equations must be either redundant or nonintersecting. This corresponds to not being able to simultaneously satisfy all climate outlook information with fewer scenarios than there are outlook boundary conditions.) Selection of some for elimination is facilitated by assigning each equation in (17) a priority reflecting its importance to the user. [The highest priority is given to the equation in (17) corresponding to (14e), guaranteeing that all relative frequencies sum to unity.] Each equation, in priority order starting with the next to highest priority, is compared to the set of all higher-priority equations and eliminated if it is redundant or does not intersect the set. By starting with the higher priorities, we ensure that each equation is compared with a known valid set of equations, and that we keep higher-priority equations in preference to lower-priority equations. Thus we can always reduce (17) so that $m \le n$. If $m = n$, then (17) can be solved via Gauss-Jordan elimination as a system of linear equations for the weights, w_i, since the equations are now independent and intersecting (in n-space). Otherwise, $m < n$, and (17) consists of the remaining independent intersecting equations.

There are multiple solutions to (17) for $m < n$, and the identification of the "best" set of weights requires the specification of a measure for comparing the solutions. One such measure is the deviation of the weights from unity, $\sum_{i=1}^{n} (w_i - 1)^2$. Solutions of (17) that give smaller values of this measure can be judged better than those that do not (and the resulting very large structured set of scenarios is more similar to the original set of scenarios in this sense). Other measures are also possible, including those using other functions expressing deviation of the weights from a goal, or measures defined on the resulting joint probability distribution function estimates (looking at similarity in joint distributions between the very large structured set and the original set). Here, it is judged desirable to be as similar to the original set as possible, in terms of relative frequencies of the selected events.

We can formulate an optimization problem to minimize the foregoing deviation of weights from unity in selecting a solution to (17)

TABLE 2. Climate Outlook Weights Using All Historical Time Series*

Year (1)	Weight (2)	Year (3)	Weight (4)	Year (5)	Weight (6)
1948	0.444378	1963	0.259718	1978	1.527387
1949	1.659873	1964	1.527387	1979	1.112034
1950	1.089694	1965	1.112034	1980	1.459070
1951	0.927374	1966	1.183255	1981	1.527387
1952	0.150880	1967	1.089694	1982	0.157130
1953	0.259718	1968	0.982324	1983	1.007623
1954	0.450628	1969	1.659873	1984	1.545569
1955	0.335539	1970	1.192282	1985	1.675279
1956	0.528100	1971	1.104530	1986	1.459070
1957	0.688826	1972	1.675279	1987	0.335539
1958	1.636225	1973	1.098279	1988	1.083444
1959	1.105783	1974	1.112034	1989	0.921124
1960	0.259718	1975	1.621390	1990	0.688826
1961	0.521850	1976	1.536542	1991	0.921124
1962	1.104530	1977	1.104530	1992	0.157130

*Solution of Eq. (18) with Fig. 3 coefficients and Method 1 in Fig. 1; a priori settings for JAS, SON, DJF, and JFM temperature probabilities are used and settings for FMA and MAM temperature probabilities and JFM precipitation probabilities are unused.

Settings*

Year (1)	Weight (2)	Year (3)	Weight (4)	Year (5)	Weight (6)
1948	0	1963	0.450000	1978	1.269962
1949	1.060486	1964	1.269962	1979	1.919873
1950	0.312190	1965	0.424136	1980	1.813411
1951	1.008031	1966	1.808557	1981	1.279712
1952	0	1967	1.879379	1982	0.171944
1953	0	1968	1.912046	1983	0.911242
1954	0	1969	2.627675	1984	1.795797
1955	0.357372	1970	0	1985	1.875076
1956	1.137376	1971	0.379306	1986	1.884862
1957	0.977323	1972	1.803624	1987	0
1958	1.355692	1973	1.724416	1988	1.737354
1959	1.264911	1974	0.424136	1989	0.767599
1960	0.025845	1975	1.297178	1990	0.977323
1961	0.825493	1976	0.366735	1991	0.839051
1962	0.460508	1977	2.522282	1992	0.082140

*Solution of Eq. (18) with Fig. 3 coefficients and method 2 in Fig. 1; all a priori settings in Fig. 3 are used.

$$\min \sum_{i=1}^{n} (w_i - 1)^2; \quad \text{subject to } e_k \sum_{i=1}^{n} a_{k,i} w_i = e_i \; k = 1, \ldots, m \tag{18}$$

By defining the Lagrangian for this problem (Hillier and Lieberman 1969)

$$L = \sum_{i=1}^{n} (w_i - 1)^2 - \sum_{k=1}^{m} \lambda_k \left(\sum_{i=1}^{n} a_{k,i} w_i - e_k \right) \tag{19}$$

(where λ_k = unit penalty of violating the kth constraint in the optimization) and by setting the first derivatives of the Lagrangian with respect to each variable to zero

$$\frac{\partial L}{\partial w_i} = 2(w_i - 1) - \sum_{k=1}^{m} \lambda_k a_{k,i} = 0, \quad i = 1, \ldots, n \tag{20a}$$

$$\frac{\partial L}{\partial \lambda_k} = -\sum_{i=1}^{n} a_{k,i} w_i + e_k = 0, \quad k = 1, \ldots, m \tag{20b}$$

we have a set of necessary but not sufficient conditions for the problem of (18). Eqs. (20*a*,*b*) are linear and solvable via the Gauss-Jordan method of elimination. Sufficiency may be checked by inspection of the solution space in the vicinity of the solution.

The solution of (18) may give positive, zero, or negative weights, but only nonnegative weights make physical sense and we must further constrain the optimization to nonnegative weights. This can be done by introducing nonnegativity inequality constraints into (18), converting them to equality constraints by defining additional variables, redefining the Lagrangian in (19) in terms of these additional constraints and variables, and determining the corresponding additional equations in (20). These additional equations would require enumeration of all zero points or "roots" of (20) (a root is a solution with zero-valued weights). However, this is computationally impractical since it can involve the inspection of many roots [e.g., for $n = 50$, there are $2^{50} - 1$ roots ($>10^{15}$)]. Furthermore, nonnegativity constraints can result in infeasibility (there is no solution). In this case, additional lowest priority equations must be eliminated from (17) to allow a nonnegative solution. The smallest number possible should be eliminated so that as many of the a priori settings as possible are preserved. Elimination of equations can proceed in a variety of manners. If higher-priority equations were eliminated, it might be possible to eliminate fewer equations. This would involve further assessment of the importance of a small set of high-priority equations versus a larger set of lower priority equations, which is impossible to make in a general manner for all situations. The following two methods provide systematic procedures for finding nonnegative weights through the elimination of lowest-priority equations. They also avoid the direct use of nonnegativity constraints in (18), thus avoiding inspection of the large number of roots that can result.

The first method guarantees that only strictly positive weights will result; this means that all possible future scenarios are used (no scenario is weighted by zero and effectively eliminated) in estimating probabilities and other parameters. The procedure is to solve (18) without additional "positivity" constraints (all weights are positive). If the solution also satisfies the positivity constraints, then we also have a solution to the further-constrained optimization problem, and we are finished. If the solution does not satisfy all the positivity constraints, then it cannot be an actual solution to the further-constrained problem. This indicates some positivity constraints are active in the actual solution and the constrained optimum may exist only in the limit as some of the weights approach zero (nonpositive). We need not solve this further-constrained problem, since that solution does not interest us. Instead, we remove the lowest-priority equation (reduce m by one) in (17) and (18) and resolve the optimization, repeating until we have a strictly positive solution. Fig. 1 summarizes the procedural algorithm for this method.

Alternatively, if we are willing to disallow some of the possible future scenarios (allow zero weights), then we can strive to satisfy more of the a priori settings [more of the equations in (17)] in the solution. In the second method, if negative weights are observed in the solution of (18), we add zero constraints ($w_i = 0$), corresponding only to those weights that are negative, and solve this further-constrained problem. However, introducing selected zero constraints will either eliminate some a priori settings [equations in (17)] (because of infeasibility but not because of redundancy) or it will not. If it does, the solution to the further-constrained problem cannot be feasible in the predecessor problem. The method instead removes the lowest-priority constraint in the predecessor problem (reduce m by one) and resolves the optimization. It it does not (eliminate some a priori settings), then the optimum solution to the further-constrained problem is feasible (and optimum) in the predecessor problem, but new negative weights could be generated. If no negative weights are generated then we are finished. If some negative weights are generated, the process (of adding selected zero constraints and solving the further-con-

Month	Quantiles									Mean	Standard deviation
	1%	5%	10%	20%	50%	80%	90%	95%	99%		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
June 1995	88	99	103	108	149	167	185	188	198	141	30
July 1995	68	80	92	101	114	142	153	166	180	120	26
August 1995	22	44	55	82	95	131	137	151	183	102	35
September 1995	−14	−5	1	39	65	109	137	157	176	75	47
October 1995	−14	−5	7	23	46	77	89	93	102	49	30
November 1995	−58	−42	−18	−14	2	30	59	66	86	10	33
December 1995	−65	−59	−50	−39	−28	−15	−1	2	16	−26	18
January 1996	−77	−65	−50	−40	−23	−15	6	8	13	−25	20
February 1996	−55	−37	−27	−22	−14	13	21	26	58	−6	23
March 1996	−27	−25	−7	5	21	59	82	92	115	34	36
April 1996	41	62	75	87	120	151	164	173	177	121	32
May 1996	94	100	104	127	159	192	228	234	246	162	42

[a]Forecast nonexceedance quantiles, mean, and standard deviation are expressed as overlake depths. The quantiles are interpolated from Eq. (9*b*) and the mean and standard deviation are from Eq. (9*c*,*d*), with the weights from Table 3. This hydrological outlook corresponds to the Climate Prediction Center "Climate Outlook" for June 1995, using probability settings on temperature for periods JAS, SON, DJF, JFM, FMA, and MAM, and on precipitation for the JFM period.

strained problem) can be repeated either until an optimum solution is generated to the further-constrained problem that is nonnegative or until a priori settings are eliminated. If the latter occurs, the method removes the lowest-priority constraint in the predecessor problem (reduce m by one) and resolves the optimization. This process is repeated until we have a nonnegative solution. Fig. 1 also summarizes the procedural algorithm for this method.

EXAMPLE CONSIDERATION OF MULTIPLE OUTLOOKS

Consider the following example. The Great Lakes Environmental Research Laboratory (GLERL) hydrology models are to be used to estimate the 12-month probabilistic outlook of net basin supply for Lake Superior beginning June 1995 by using the NOAA Climate Prediction Center "Climate Outlook" for June 1995. (Net basin supply is the algebraic sum of overlake precipitation, lake evaporation, and basin runoff to the lake.) The outlook will be made by identifying all 12-month meteorological time series that start in June from the available historical record of 1948–93; there are 45 such times series for each meteorological variable. The time series for all meteorological variables will be used in simulations with GLERL's hydrology models and current initial conditions to estimate the 45 associated time series for each hydrological variable. Each set of historical meteorological and associated hydrological time series, corresponding to each segment of the historical record, represent a possible future scenario. The 45 scenarios will be used as a statistical sample in an operational hydrology approach to make the probabilistic outlook. We will incorporate the Climate Prediction Center "Climate Outlook" by using selected period outlook settings as boundary conditions in the determination of weights to apply to our scenario set. We use these weights, through estimates from (9), to make our probabilistic outlook.

We must begin by abstracting historical quantiles of air temperature and precipitation for the Lake Superior basin; these are presented in Table 1 for the periods of interest in making the June outlook. These were estimated from the 1961–90 period in accordance with definitions provided by the Climate Prediction Center for use of their climate outlooks. These quantile estimates are the basis for interpretation of the Climate Prediction Center's climate outlooks.

The NOAA Climate Prediction Center "Climate Outlook" for June 1995 (made May 18, 1995) over the Lake Superior Basin is given in Fig. 2 in columns two and three. They are interpreted, in accordance with specifications of the Climate Prediction Center [and as described in the section on "Meteorological Probability Outlooks" and in the previous section; see (12)], to construct the probabilities associated with the reference quantiles in Table 1; these are given in columns four through nine in Fig. 2. The shaded entries in Fig. 2 denote outlook probabilities designated as significant by the Climate Prediction Center, who suggest that the remainder be estimated from climatology since they have insufficient skill to make outlooks in those cases.

The highlighted entries in Fig. 2 are used arbitrarily, in priority of their appearance, to make the hydrological outlook. These seven outlook settings and the reference quantiles in Table 1 are used with inspection of all 45 scenarios to construct the 15 equations represented by (17) in Fig. 3. Table 2 presents the solution of these equations, found by minimizing the deviation of weights from unity, as in (18), by using the first procedural algorithm in Fig. 1 (using all scenarios). While all 45 scenarios are used (all weights are strictly positive), not all of the selected a priori climate settings can be used. The temperature probability settings for JAS, SON, DJF, and JFM were used while the temperature probability settings for FMA and MAM and the precipitation probability setting for JFM were unused.

Table 3 presents the solution of the equations with coefficients in Fig. 3, found by minimizing the deviation of weights with unity, as in (18), by using the second procedural algorithm in Fig. 1 (maximizing use of the a priori climate outlook settings). All seven a priori climate settings, highlighted in Fig. 2, can be included. Table 3 shows that six weights were assigned values of zero to enable this inclusion. This means that the scenarios starting in June 1948, 1952, 1953, 1954, 1970, and 1987 are unused in the ensuing probabilistic outlook.

Finally, as an example for one hydrological variable, the probabilistic outlook for net basin supply (NBS), over the 12 months from June 1995 through May 1996, is given in Table 4. There were 45 values of monthly NBS, corresponding to the 45 scenarios used in the simulation, for each of the 12 months. Each value was multiplied by its respective weight from Table 3, as in (9), to compute various statistics for the probabilistic outlook each month. Selected quantiles from the forecast NBS probability distribution and the mean and standard deviation for each month of the outlook are displayed in Table 4. Since the weights of Table 3 were used, the probabilistic outlook in Table 4 represents use of all selected a priori climate outlook settings.

CONCLUSIONS

The operational hydrology approach described here uses all (method 1) or most (method 2) historical information while preserving many of the long-term meteorological probability outlooks provided by NOAA's Climate Prediction Center. Some other approaches severely limit the use of historical data to be compatible with climate outlooks or use all historical data only by ignoring these outlooks. The use of a hypothetical very large structured set of scenarios (matching climate outlooks) to estimate hydrological outlook probabilities corresponds to the use of the weighted original set of possible future scenarios estimated from the historical record. (Each scenario consists of an actual segment of the historical meteorological record and its associated hydrological transformation made with appropriate models.) The building of this hypothetical very large structured set is an arbitrary concept that was useful in defining the weights. The National Weather Service is now considering weighting methods for their Extended Streamflow Prediction (ESP) operational hydrology approach (Day 1985; Smith et al. 1992) that couple historical time series of precipitation with precipitation forecasts (Ingram et al. 1995).

Still other approaches use time series models, fit to historical data, to generate a large sample, increasing precision but not accuracy in the resulting statistical estimates. Direct use of the historical record to build a sample avoids the loss of representation consequent with time series models. In addition, it may not be clear how to modify time series models to agree with climatic outlooks and still be representative of the underlying behavior originally captured in the time series models. Nevertheless, if time series models are used in building the sample, weighting of this sample, in the manner described here, to agree with climatic outlooks is straightforward and still could be used.

The determination of these weights involves several choices also made arbitrarily here. For example, the weights could be determined directly from multiple climate outlooks, as exemplified in Appendix I for a single climate outlook. This would involve restrictions on the multiple climate outlooks not considered in this paper. The formulation of an optimization problem, used here, allows for a more general approach in determining these weights in the face of multiple outlooks. However, this formulation also involves arbitrary choices, the largest of which is the selection of a relevant objective function. As mentioned earlier, other measures of relevance of the weights to a goal are possible and could require reformulation of the solution methodology. An early approach, not reported here, minimized the sum of squared differences between the relative frequencies associated with the bivariate distribution of precipitation and temperature before and after application of the weights. The goal was to make the resulting joint distribution as similar as possible to that observed historically while making the marginal distributions match the climate outlooks. Unfortunately, the method was intractable for consideration of more than one climate outlook.

Also not reported in this paper was an effort where consideration was made of linear objective functions; the weights were linearly related to a goal of making them as close as possible to unity. This was an effort to make the optimization problem amenable to linear programming solution methodologies. That way, additional constraints on the weights for positivity or nonnegativity could be added directly to the optimization and evaluated systematically. The Simplex method (Wagner 1975) was used to solve the resulting linear optimization problem. However, the large number of roots consequent in practical problems for a nonunique optimum still rendered the solution computationally intractable. Nevertheless, this formulation could be used in the manner described for the solution to (20) (where positivity or nonnegativity constraints are considered ...) without loss of generality, if a linear objective function was deemed more suitable in an application.

An important advantage associated with the computation of a weighted sample in the operational hydrology approach described here, and as with ESP, is the independence of the weights and the hydrology models. After model simulations are made to build a set of possible future scenarios for analysis, several probabilistic outlooks can be generated with weights corresponding to the use of different climate outlooks, different methods of considering the climate outlooks, and alternative selections of just which of the 14 outlooks that are available each month to use. In making these alternative analyses and weights (re)computations, it is unnecessary to redo the model simulations to rebuild the set. This is a real savings when the model simulations are extensive, as is the case with Great Lakes hydrological outlooks. This also enables efficient consideration of other ways of using the weights to make probabilistic outlooks. For example, our use of nonparametric statistics in (9) restricts the range of any variable to that present in the historical record or in their hydrological transformations. An alternative that does not restrict range in this manner is to hypothesize a distribution family (e.g., normal, log-normal, log-Pearson type III) and to estimate its moments by using sample statistics defined analogously to those in (9). The detractor for parametric estimation is hypothesizing the family of distributions to use.

Most significantly, the method allows joint consideration of multiple meteorological outlooks defined over different lengths and periods of time. It can be easily extended to incorporate consideration of six- to 14-day outlooks, for which there is relatively greater skill, as well as other period outlooks.

Computer code is available, to make all computations (outside of the hydrological modeling), for use by others in utilizing the NOAA Climate Prediction Center "Climate Outlook." The code finds all necessary reference quantiles, for using a climate outlook, from a user-supplied file of historical daily air temperature and precipitation, sets up all equations in (17), formulates the optimization problem of (18), and performs the sequential optimizations [solutions of (20)] with either method in Fig. 1 (either use all historical data or maximize use of a priori climate outlook settings). The code is available both as a stand-alone FORTRAN implementation, for use under a variety of operating systems, and as a specially designed user interface Windows application. The latter also allows readily understandable user interpretation of the NOAA Climate Prediction Center's "Climate Outlooks" and easy user assignment of relevant priorities.

ACKNOWLEDGMENTS

Discussions with Lynn Herche focused the resampling and empirical distribution material. This is GLERL contribution number 969.

APPENDIX I. ALTERNATIVE CONSIDERATION OF A SINGLE CLIMATE OUTLOOK

Consider probability estimates for a single variable that match a priori settings. For example, suppose that our a priori settings for average temperature during the June-July-August climate outlook (or JJA) T_{JJA} are a 38.3% chance of exceeding the 66.7% quantile (determined for JJA within 1961–90) $\tau_{JJA,0.667}$, a 28.3% chance of not exceeding the 33.3% quantile $\tau_{JJA,0.333}$, and a 33.4% chance of being between the two

$$\hat{P}[T_{JJA} > \tau_{JJA,0.667}] = 0.383, \text{ over the upcoming outlook period} \quad (21a)$$

$$\hat{P}[T_{JJA} \leq \tau_{JJA,0.333}] = 0.283, \text{ over the upcoming outlook period} \quad (21b)$$

$\hat{P}[\tau_{JJA,0.333} < T_{JJA} \le \tau_{JJA,0.667}] = 0.334,$

over the upcoming outlook period (21c)

where $\hat{P}$ = relative frequency, used as a probability estimate; and the quantiles are defined from historical data

$$\hat{P}[T_{JJA} \le \tau_{JJA,0.667}] = 0.667, \text{ over the historical 1961–90 period} \quad (22a)$$

$$\hat{P}[T_{JJA} \le \tau_{JJA,0.333}] = 0.333, \text{ over the historical 1961–90 period} \quad (22b)$$

We will construct a very large structured set, of size N, of scenarios with relative frequencies satisfying (21) by duplicating original scenarios, such that

$$\frac{N_U}{N} = \hat{P}[T_{JJA} > \tau_{JJA,0.667}] = 0.383 \quad (23a)$$

$$\frac{N_L}{N} = \hat{P}[T_{JJA} \le \tau_{JJA,0.333}] = 0.283 \quad (23b)$$

$$\frac{N - N_U - N_L}{N} = \hat{P}[\tau_{JJA,0.333} < T_{JJA} \le \tau_{JJA,0.667}] = 0.334 \quad (23c)$$

where N_U = number of scenarios with $T_{JJA} > \tau_{JJA,0.667}$; and N_L = number of scenarios with $T_{JJA} \le \tau_{JJA,0.333}$. The original sample of n scenarios has n_U scenarios with $T_{JJA} > \tau_{JJA,0.667}$ and n_L scenarios with $T_{JJA} \le \tau_{JJA,0.333}$. Each of the n_U scenarios will be duplicated N_U/n_U times and each of the n_L scenarios will be duplicated N_L/n_L times. By making the structured set sufficiently large, the approximations in (23) can be made as close as desired. In the limit, as the integers N, N_U, and N_L grow, the approximations in (23) approach equalities.

Of the original n scenarios, the ith scenario is repeated r_i times, where

$$r_i = \frac{N_L}{n_L}, \forall\, i \mid t_{JJA,i} \le \tau_{JJA,0.333} \quad (24a)$$

$$r_i = \frac{N_U}{n_U}, \forall\, i \mid t_{JJA,i} > \tau_{JJA,0.667} \quad (24b)$$

$$r_i = \frac{N - N_U - N_L}{n - n_U - n_L}, \forall\, i \mid \tau_{JJA,0.333} < t_{JJA,i} \le \tau_{JJA,0.667} \quad (24c)$$

where $t_{JJA,i}$ = average JJA air temperature in scenario i. For N sufficiently large, each ratio, r_i, is an integer if the probability estimate settings are specified only to a fixed number of digits. Statistics can be written as functions of either the very large structured set $(x_1^N, \ldots, x_N^N)$, or the original set $(x_1^n, \ldots, x_n^n)$. For example, the structured sample mean and variance, $\bar{x}$ and S^2, respectively, are

$$\bar{x} = \frac{1}{N}\sum_{k=1}^{N} x_k^N = \frac{1}{N}\sum_{i=1}^{n} r_i x_i^n = \frac{1}{n}\sum_{i=1}^{n} w_i x_i^n \quad (25a)$$

$$S^2 = \frac{1}{N}\sum_{k=1}^{N} (x_k^N - \bar{x})^2 = \frac{1}{N}\sum_{i=1}^{n} r_i (x_i^n - \bar{x})^2 = \frac{1}{n}\sum_{i=1}^{n} w_i (x_i^n - \bar{x})^2 \quad (25b)$$

where

$$w_i = \frac{n}{N} r_i = 0.283\,\frac{n}{n_L}, \forall\, i \mid t_{JJA,i} \le \tau_{JJA,0.333} \quad (26a)$$

$$w_i = \frac{n}{N} r_i = 0.383\,\frac{n}{n_U}, \forall\, i \mid t_{JJA,i} > \tau_{JJA,0.667} \quad (26b)$$

$$w_i = \frac{n}{N} r_i = 0.334\,\frac{n}{n - n_U - n_L}, \forall\, i \mid \tau_{JJA,0.333} < t_{JJA,i} \le \tau_{JJA,0.667} \quad (26c)$$

If the period 1961–90 was also our entire historical record then, by definition, $n_L/n = 0.333$ and $n_U/n = 0.333$. Therefore

$$w_i = 0.283/0.333 = 0.850, \forall\, i \mid t_{JJA,i} \le \tau_{JJA,0.333} \quad (27a)$$

$$w_i = 0.383/0.333 = 1.150, \forall\, i \mid t_{JJA,i} > \tau_{JJA,0.667} \quad (27b)$$

$$w_i = 0.334/0.334 = 1.000, \forall\, i \mid \tau_{JJA,0.333} < t_{JJA,i} \le \tau_{JJA,0.667} \quad (27c)$$

Other statistics can be similarly derived. Furthermore, the preceding development can be made for variables besides temperature and for any period other than JJA without loss of generality, including single-month periods. It is also possible to define alternative very large structured sets based on other probability quantiles besides the two used here, 33.3% and 66.7%, and on other systematic manners of duplicating the original scenarios.

APPENDIX II. REFERENCES

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APPENDIX III. NOTATION

The following symbols are used in this paper:

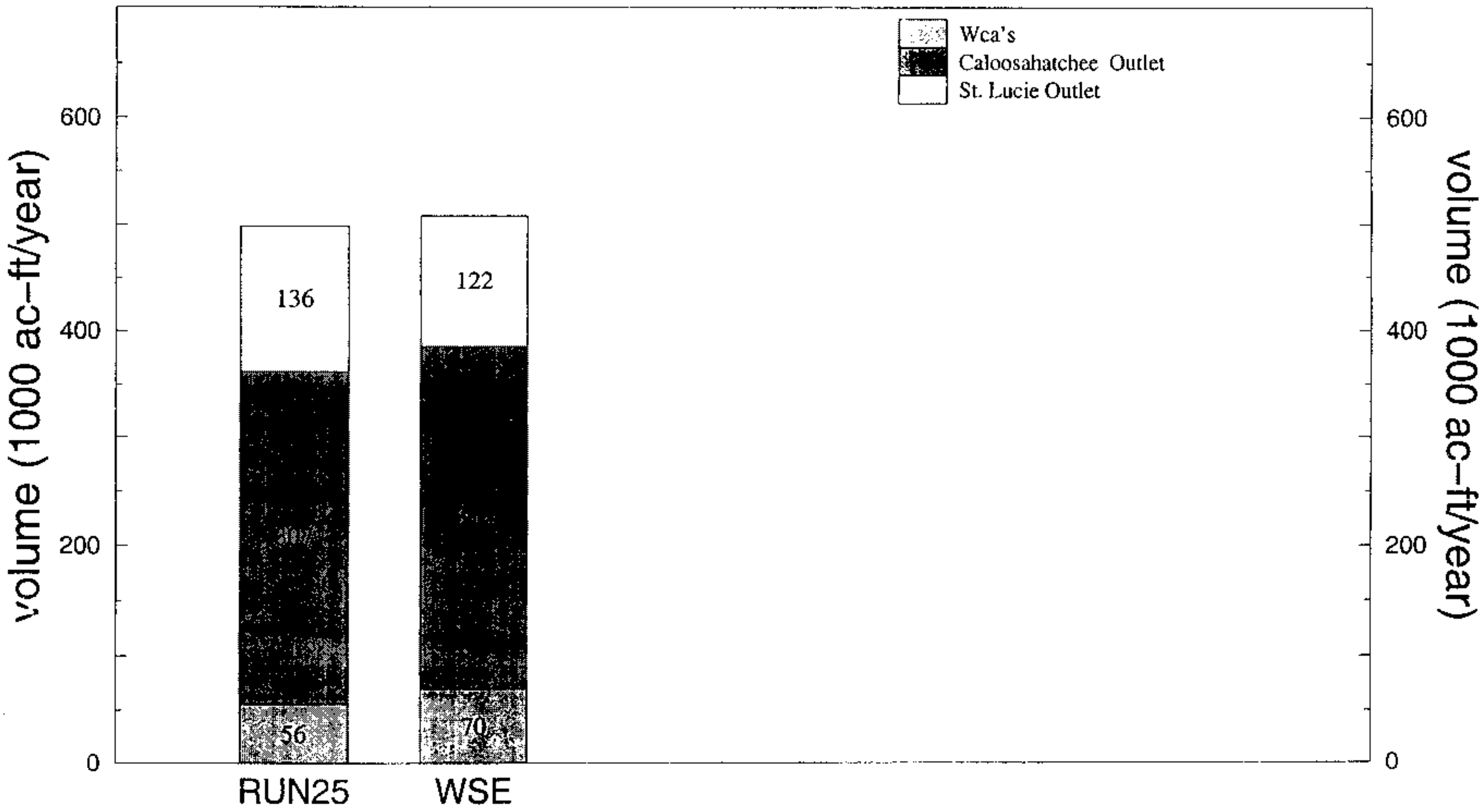
A_g = set of indices of scenarios containing average air temperature for period g in the upper third of its 1961–90 range;
a_g = a priori climate outlook probability setting for average air temperature for period g in the upper third of its 1961–90 range;
$a_{k,i}$ = coefficient in kth equation on ith weight (for ith scenario) in Eqs. (15), (17), (18), (19), and (20);
B_g = set of indices of scenarios containing average air temperature for period g in the lower third of its 1961–90 range;
b_g = a priori climate outlook probability setting for average air temperature for period g in the lower third of its 1961–90 range;
C_g = set of indices of scenarios containing average precipitation for period g in the upper third of its 1961–90 range;
c_g = a priori climate outlook probability setting for average precipitation for period g in the upper third of its 1961–90 range;
D_g = set of indices of scenarios containing average precipitation for period g in the lower third of its 1961–90 range;
d_g = a priori climate outlook probability setting for average precipitation for period g in the lower third of its 1961–90 range;
e_k = selected weights sum limit in kth Eq. in (15), (17), (18), (19), and (20), corresponding to an a priori climate outlook probability setting;
L = objective function (the Lagrangian) for an unconstrained optimization reformulated from the objective function for a constrained optimization by incorporating the constraints;
m = number of a priori settings associated with climate outlook information to be used to constrain the operational hydrology outlook;
N = number of duplicated scenarios in the hypothetical very large structured set used for statistical estimation in the operational hydrology outlook;
N_L = number of duplicated scenarios, in the hypothetical very large structured set used for statistical estimation in the operational hydrology outlook, which have $T_{JJA} \le \tau_{JJA,0.333}$ in Appendix I;
N_U = number of duplicated scenarios, in the hypothetical very large structured set used for statistical estimation in the operational hydrology outlook, which have $T_{JJA} > \tau_{JJA,0.667}$ in Appendix I;
n = number of scenarios available for use in generating the operational hydrology outlook;
n_L = number of scenarios, available for use in generating the operational hydrology outlook, which have $T_{JJA} \le \tau_{JJA,0.333}$ in Appendix I;
n_U = number of scenarios, available for use in generating the operational hydrology outlook, which have $T_{JJA} > \tau_{JJA,0.667}$ in Appendix I;
$P[\,]$ = probability of the event in brackets;
$\hat{P}[\,]$ = relative frequency in a set, of the event in brackets, used as a probability estimate;
Q_g = total precipitation over period g;
$q_{g,i}$ = total precipitation in period g of scenario i;
r_i = duplication count for ith scenario in the original set of possible future scenarios for the hypothetical very large structured set;
S^2 = estimate of variance for variable X;
T_g = average air temperature over period g;
$t_{g,i}$ = average air temperature in period g of scenario i;
w_i = weight applied to ith scenario in the original set of possible future scenarios for calculation of statistics for an operational hydrology outlook;
X = a meteorological or hydrological variable;
x_k^N = value for variable X in kth duplicated scenario in the hypothetical very large structured set of N scenarios;
x_i^n = value for variable X in ith scenario in the original set of n possible future scenarios;
$\bar{x}$ = estimate of mean for variable X;
y_m^N = mth ordered value for variable X, corresponding to kth duplicated scenario in the hypothetical very large structured set of N scenarios;
y_j^n = jth ordered value for variable X, corresponding to ith scenario in the original set of n possible future scenarios;
$\theta_{g,\gamma}$ = reference total precipitation γ-probability quantile for period g;
λ_k = Lagrange multiplier, representing the penalty associated with violation of the kth constraint equation in the optimization;
ξ_γ = reference γ-probability quantile for variable X;
$\tau_{g,\gamma}$ = reference average air temperature γ-probability quantile for period g; and
Ω = set of indices of scenarios.

Appendix G

Performance Measures Graphics for the WSE Implementation Guidelines (1995 Infrastructure and Water Use Levels)

Performance Measures for
Lake Okeechobee

Mean Annual Flood Control Releases from Lake Okeechobee for the 31 yr (1965 – 1995) Simulation



Note: Although regulatory (flood control) discharges are summarized here in mean annual values, they do not occur every year. Typically they occur in 2–4 consecutive years and may not occur for up to 7 consecutive years.

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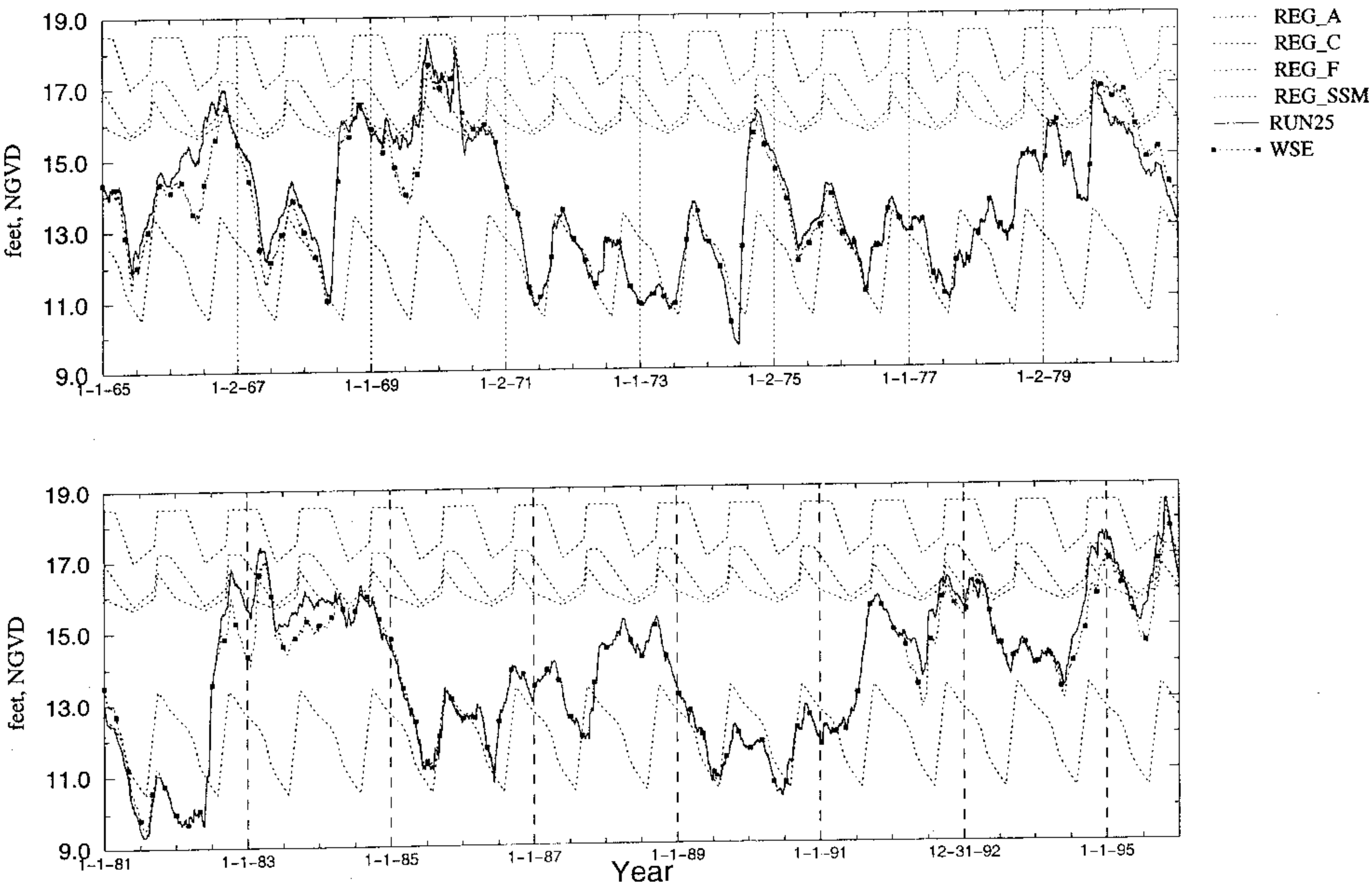
For Planning Purposes Only
SFWMM V3.6P

Daily Stage Hydrographs for Lake Okeechobee



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For Planning Purposes Only
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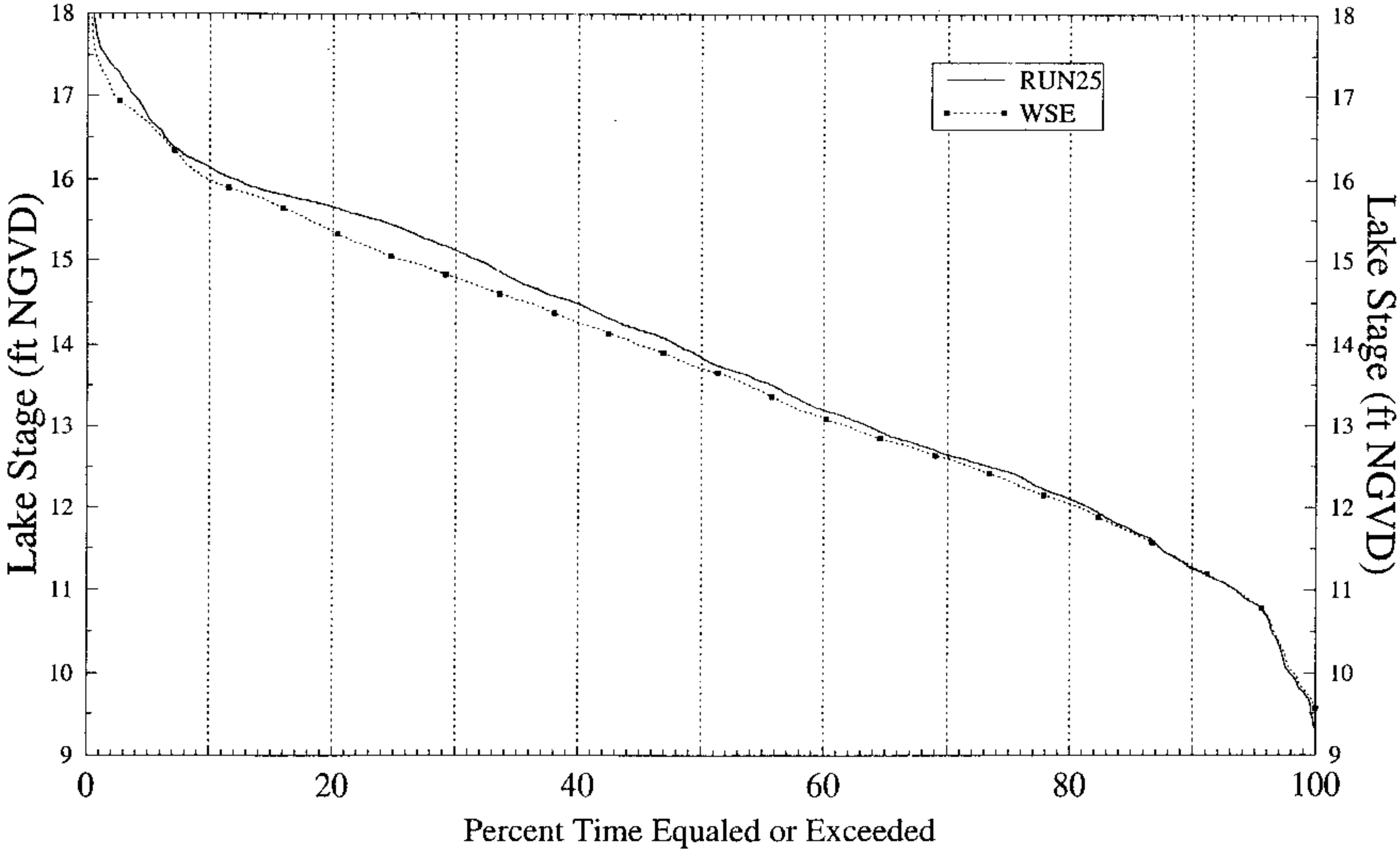
Lake Okeechobee Stage Duration Curves



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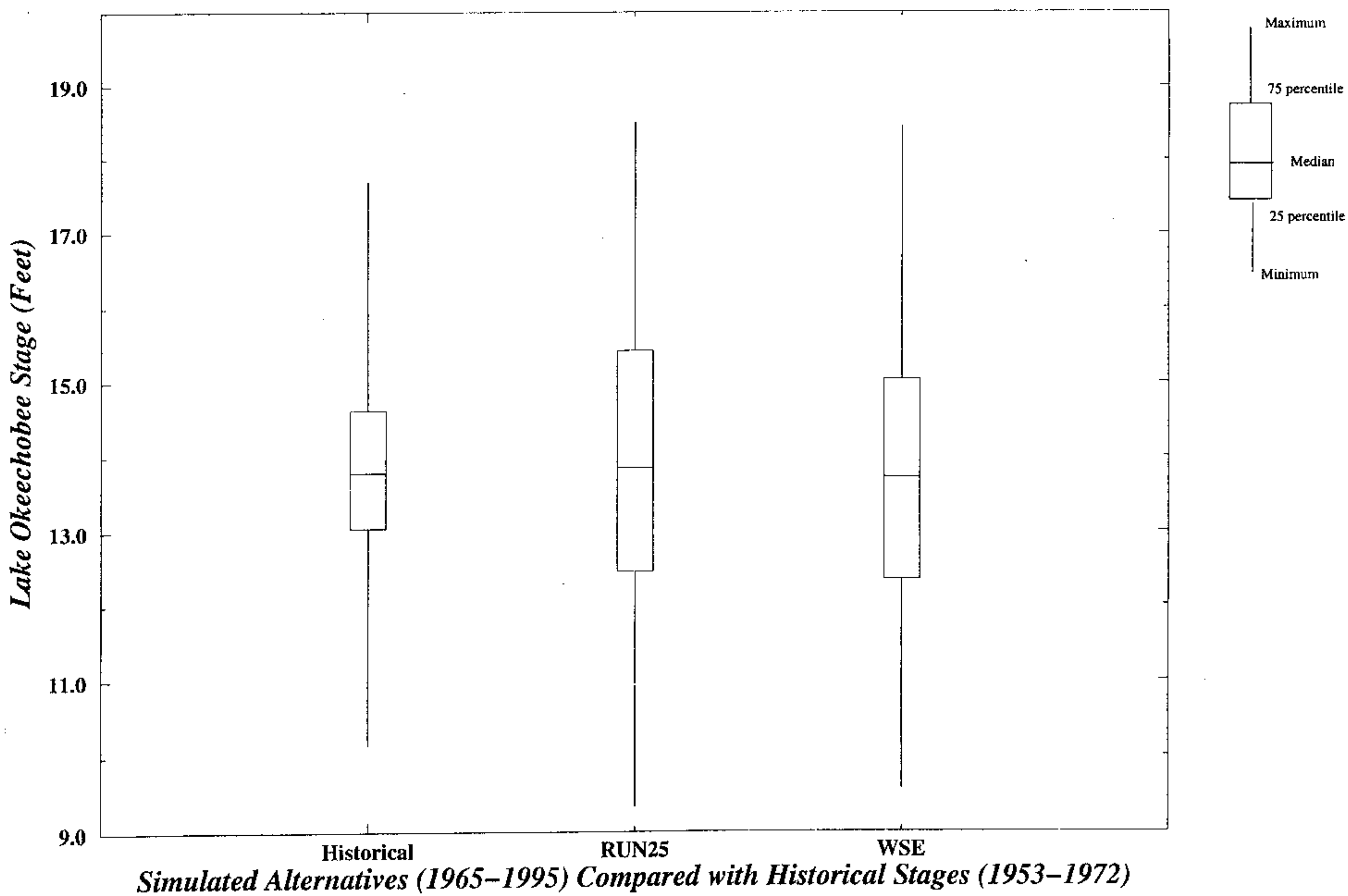
Lake Okeechobee Littoral Zone – Similarity in Lake Stages



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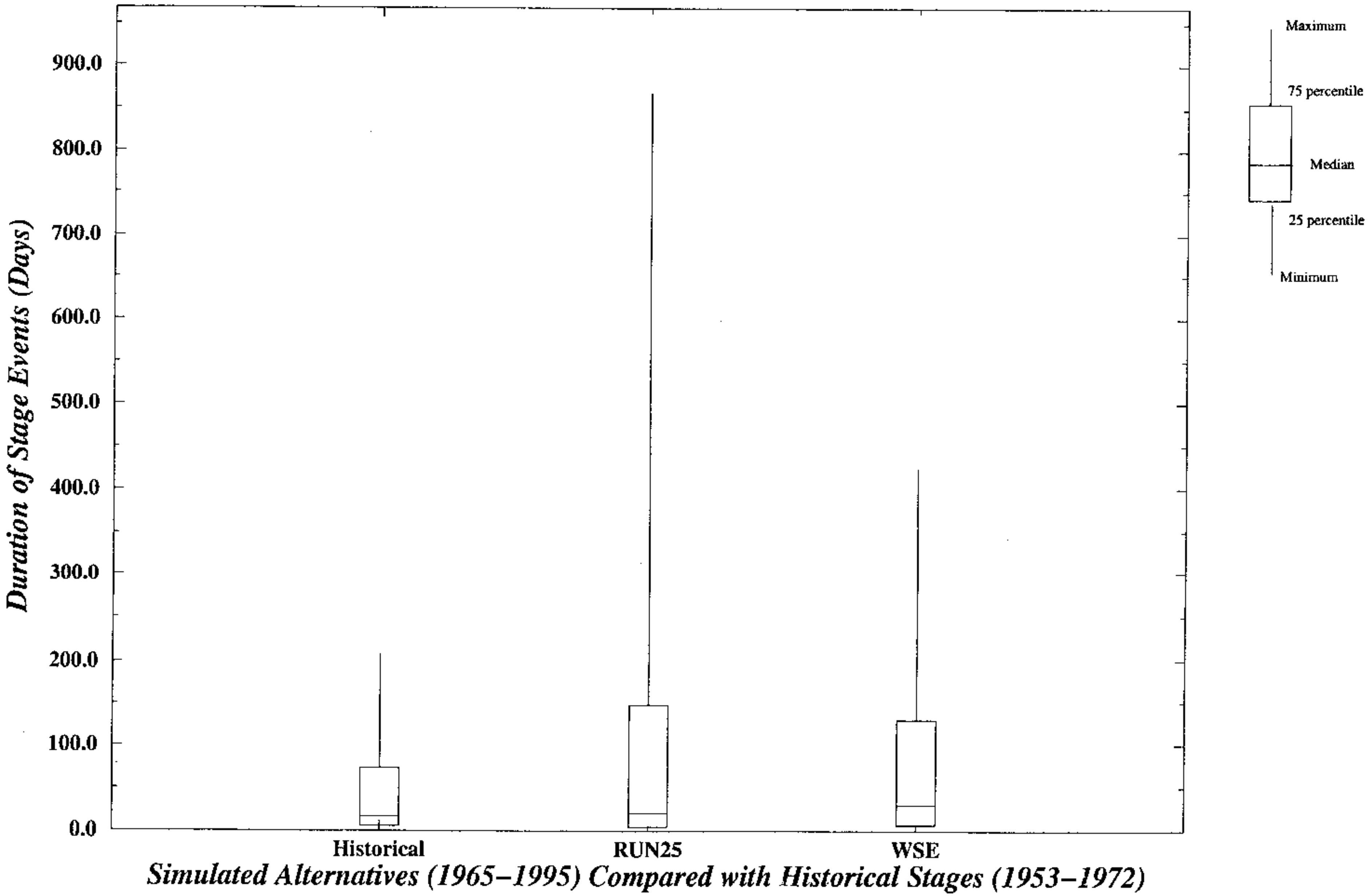
For Planning Purposes Only
SFWMM V3.6P

Lake Okeechobee Littoral Zone

Similarity in Duration of Stage Events > 15 feet



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For Planning Purposes Only
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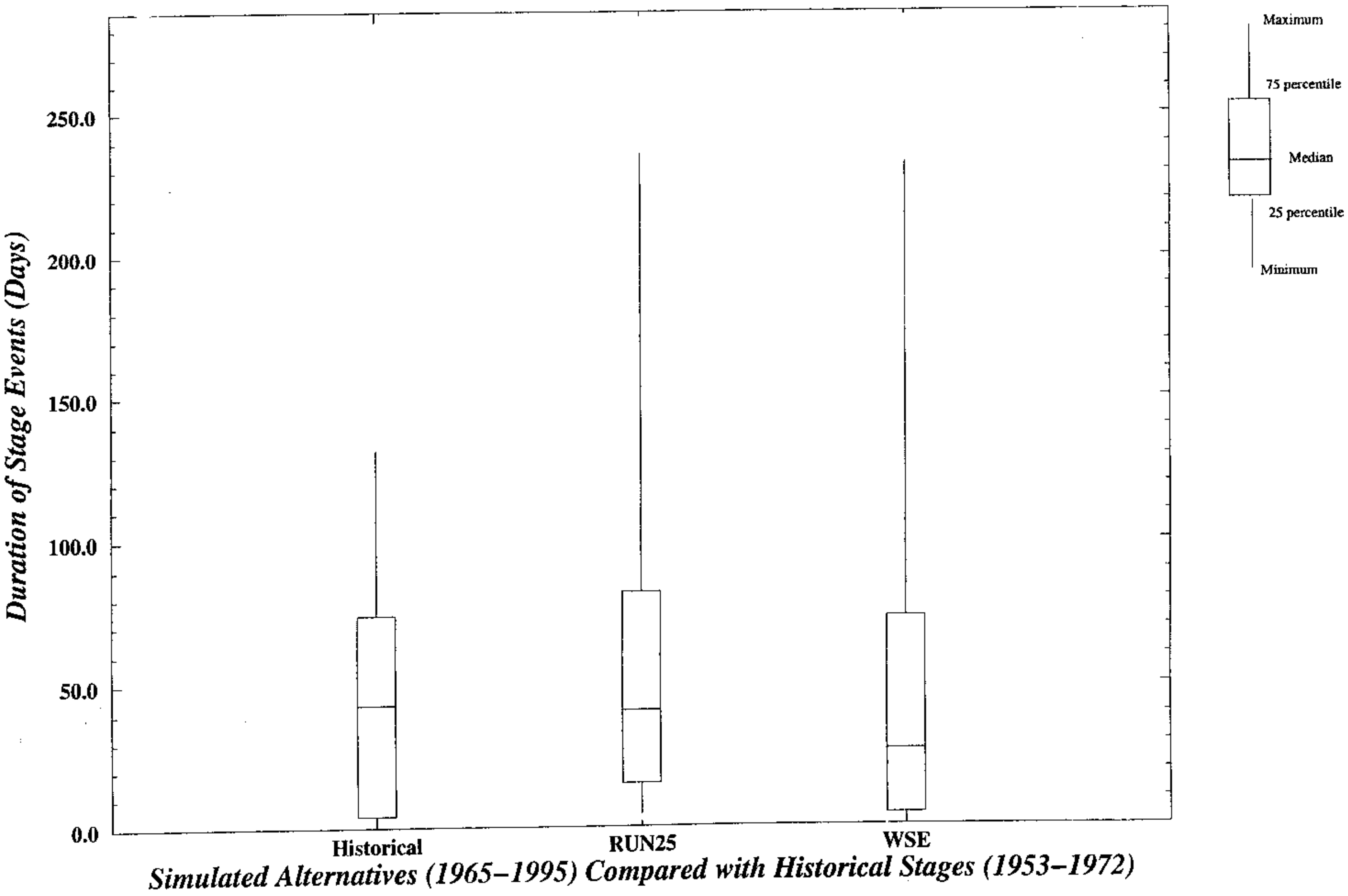
Lake Okeechobee Littoral Zone

Similarity in Duration of Stage Events < 11 feet



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For Planning Purposes Only
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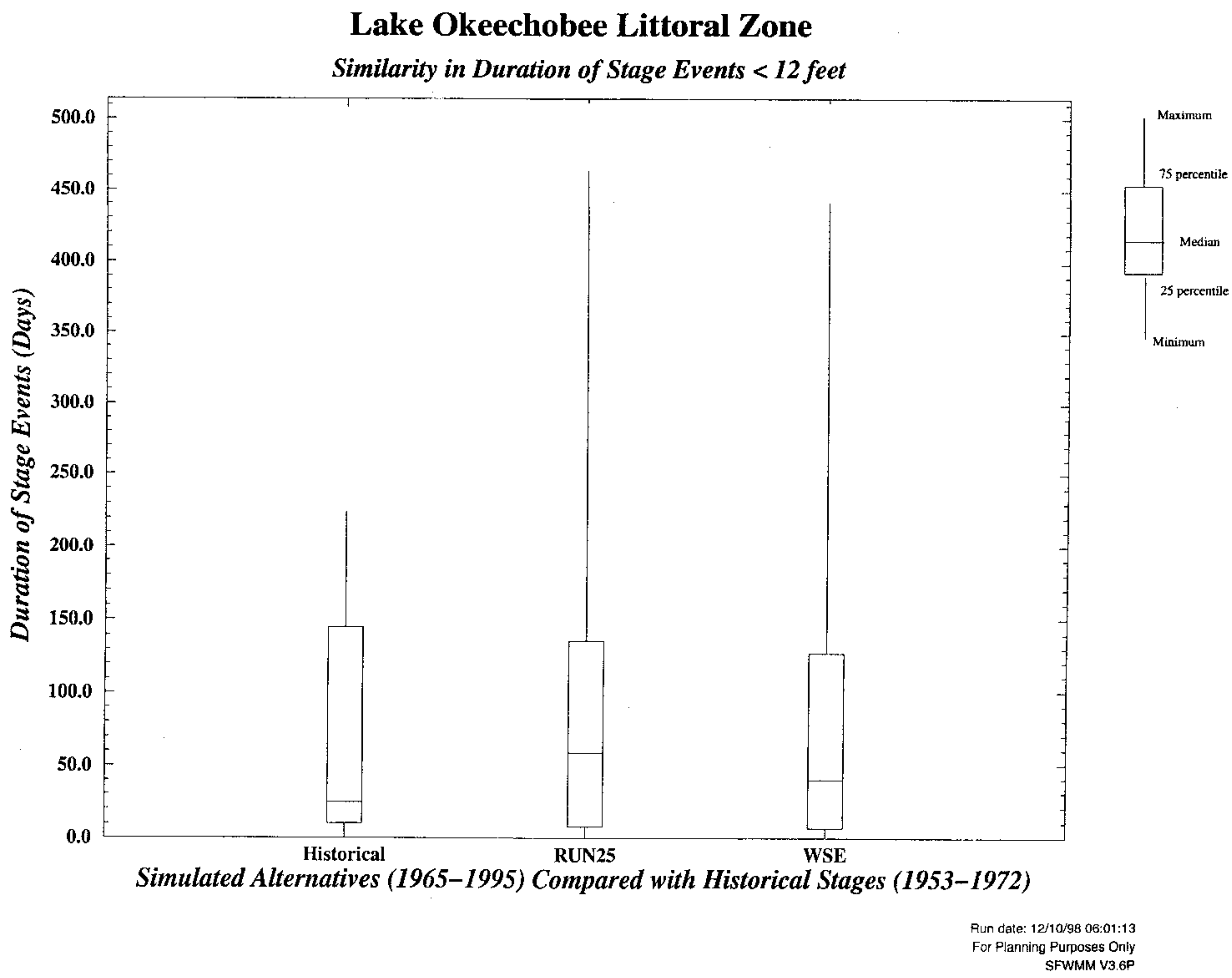
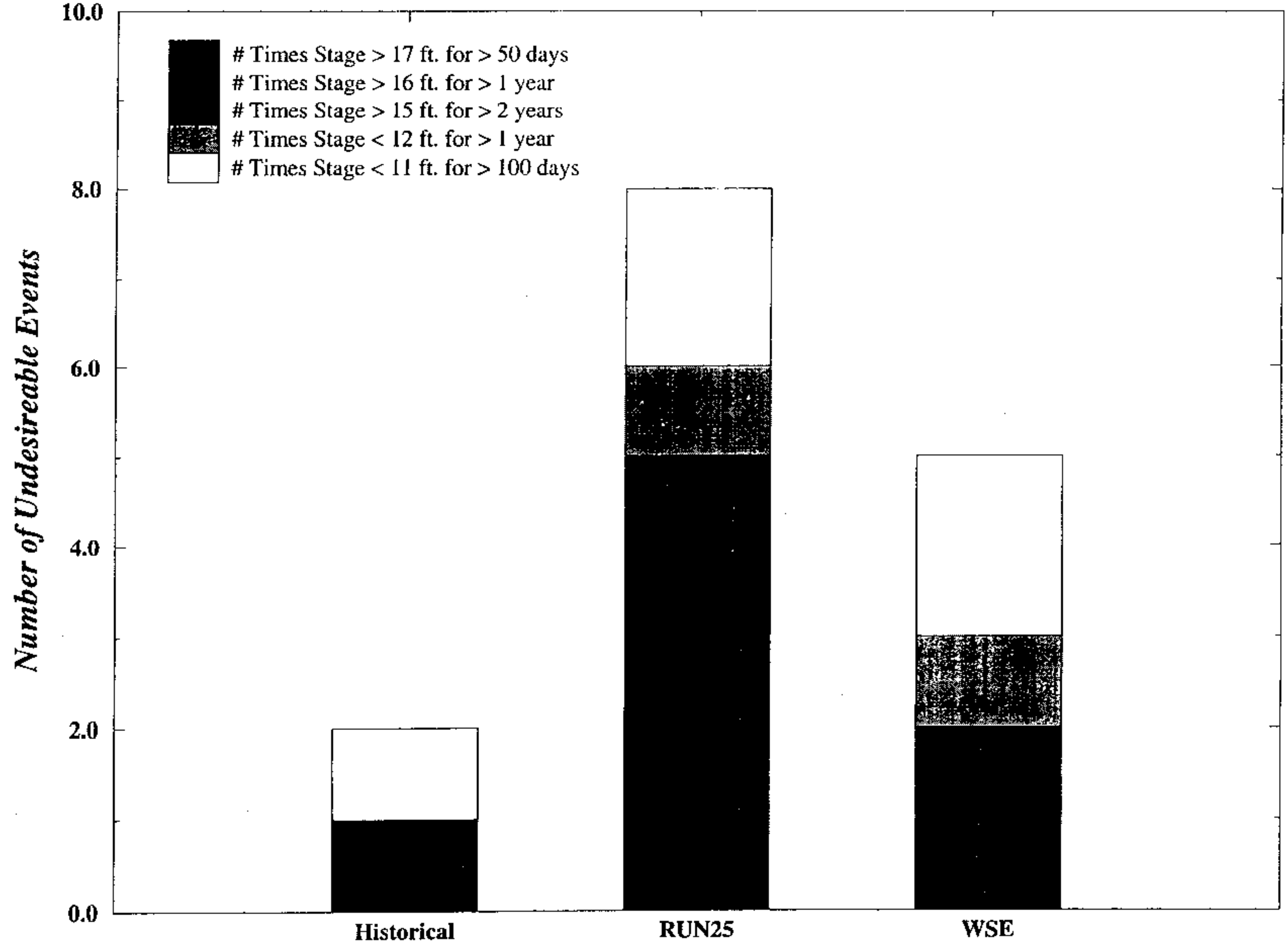

Lake Okeechobee Littoral Zone
Similarity in Duration of Stage Events < 12 feet
Duration of Stage Events (Days)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Historical
RUN25
WSE
Simulated Alternatives (1965–1995) Compared with Historical Stages (1953–1972)
Maximum
75 percentile
Median
25 percentile
Minimum
Run date: 12/10/98 06:01:13
For Planning Purposes Only
SFWMM V3.6P

Number of Undesireable Lake Okeechobee Stage Events



Simulated Alternatives (1965–1995) Compared with Historical Stages (1953–1972)

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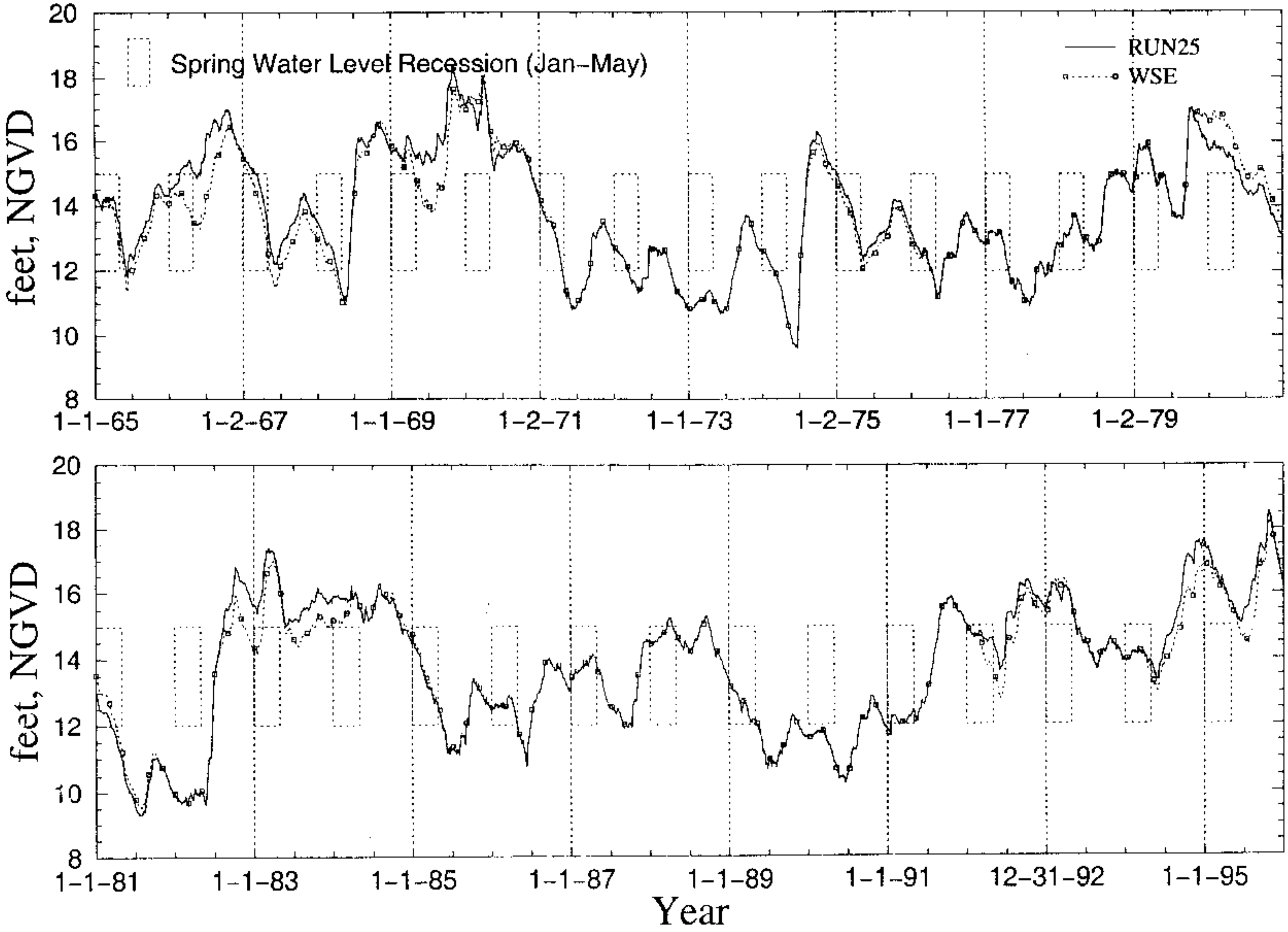
SFWMM V3.6P

Daily Stage Hydrographs for Lake Okeechobee
Spring Water Level Recession Windows



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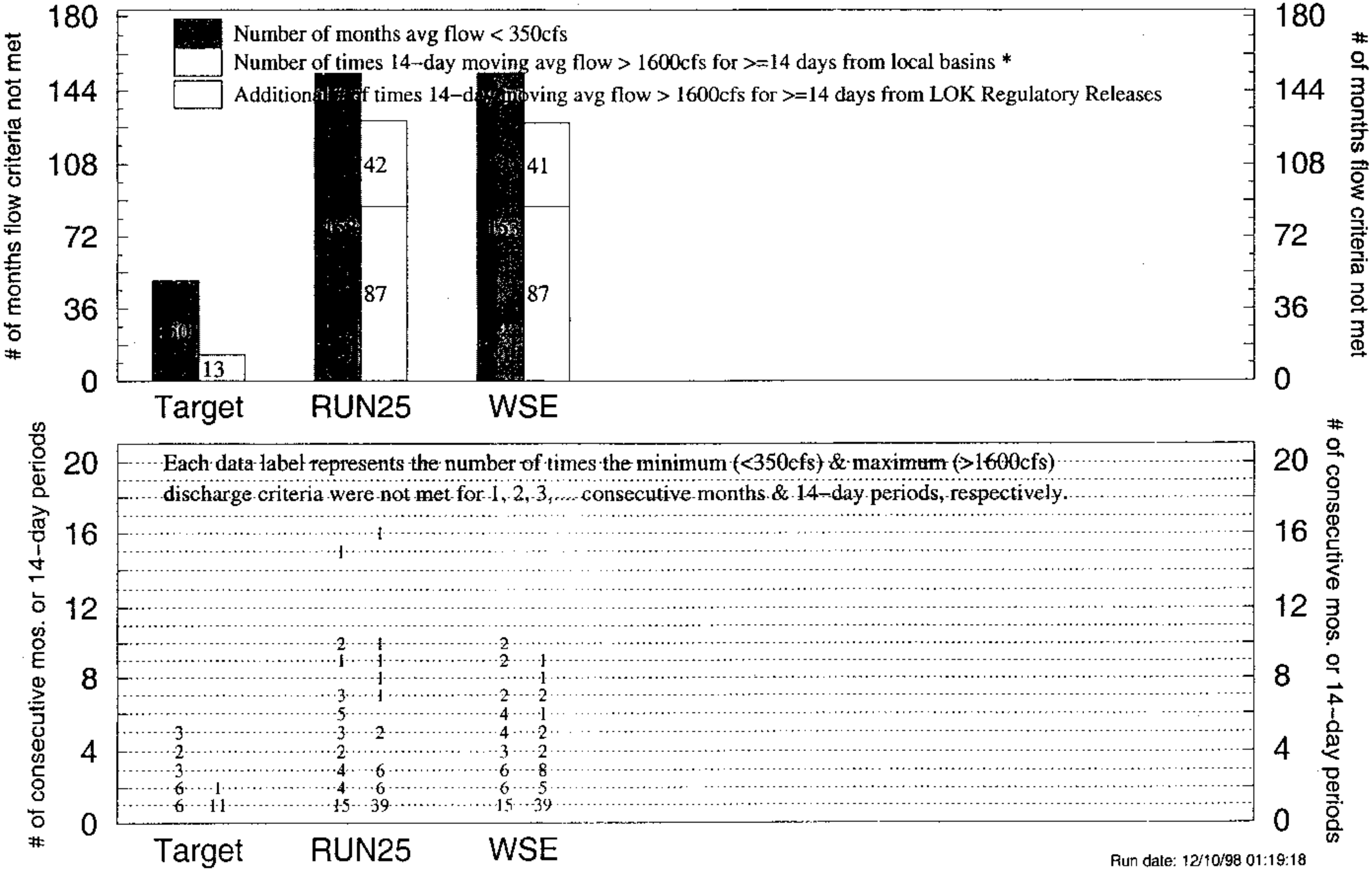
SFWMM V3.6P

Performance Measures for the

Caloosahatchee and St. Lucie Estuaries

Number of times Salinity Envelope Criteria were NOT met for the St. Lucie Estuary



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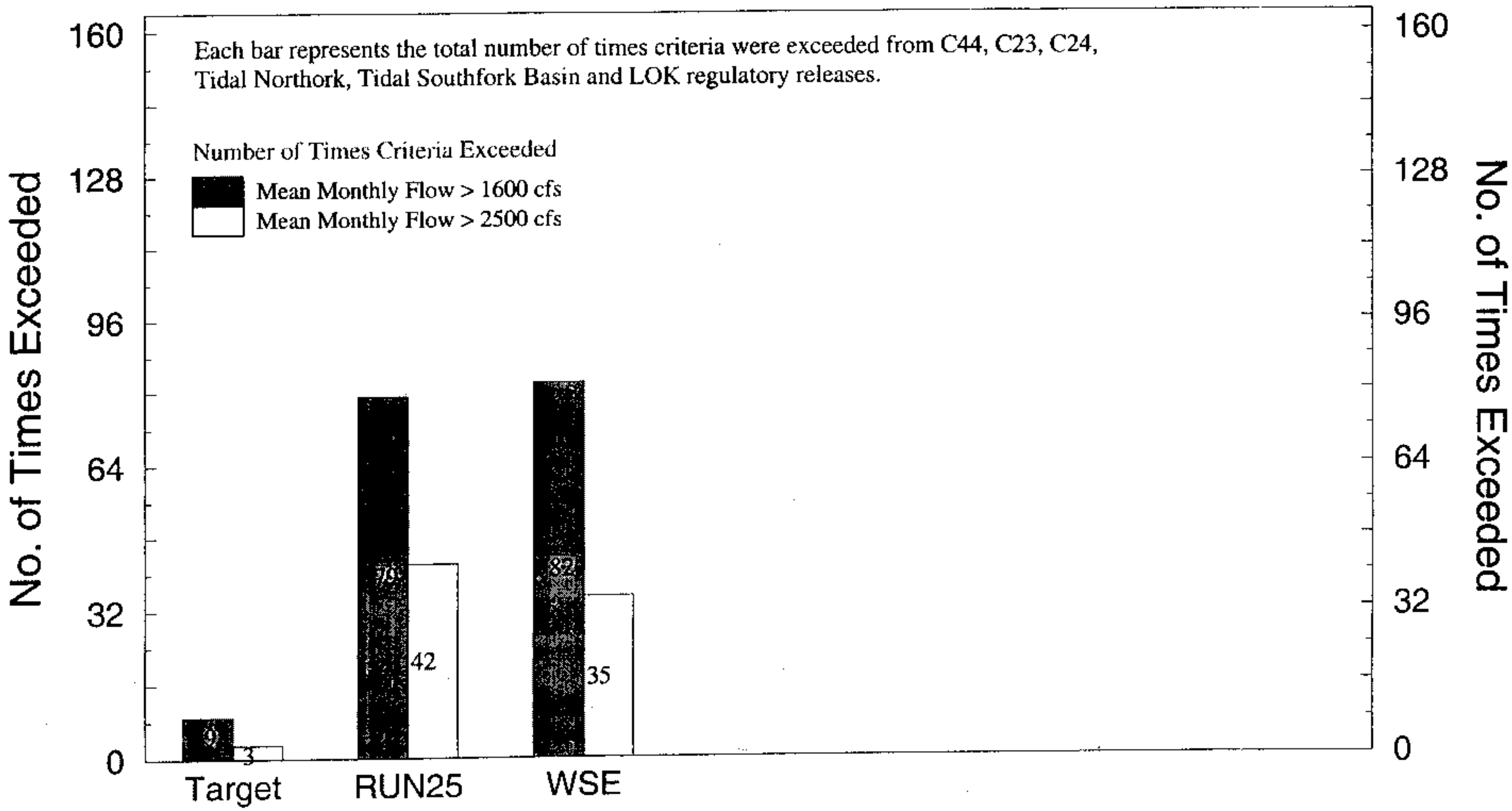
. For Planning Purposes Only
SFWMM V3.6P

Note: local basins include the C-44, C-23, C-24, North Fork and South Fork Basins

Number of Times High Discharge Criteria (mean monthly flows > 1600 & 2500 cfs) were exceeded for the St. Lucie Estuary



Note: A favorable maximum monthly flow was developed for the estuary (1600 cfs) that will theoretically provide suitable salinity conditions which promote the development of important benthic communities (eg. oysters & shoalgrass). Mean monthly flows above 2500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota.

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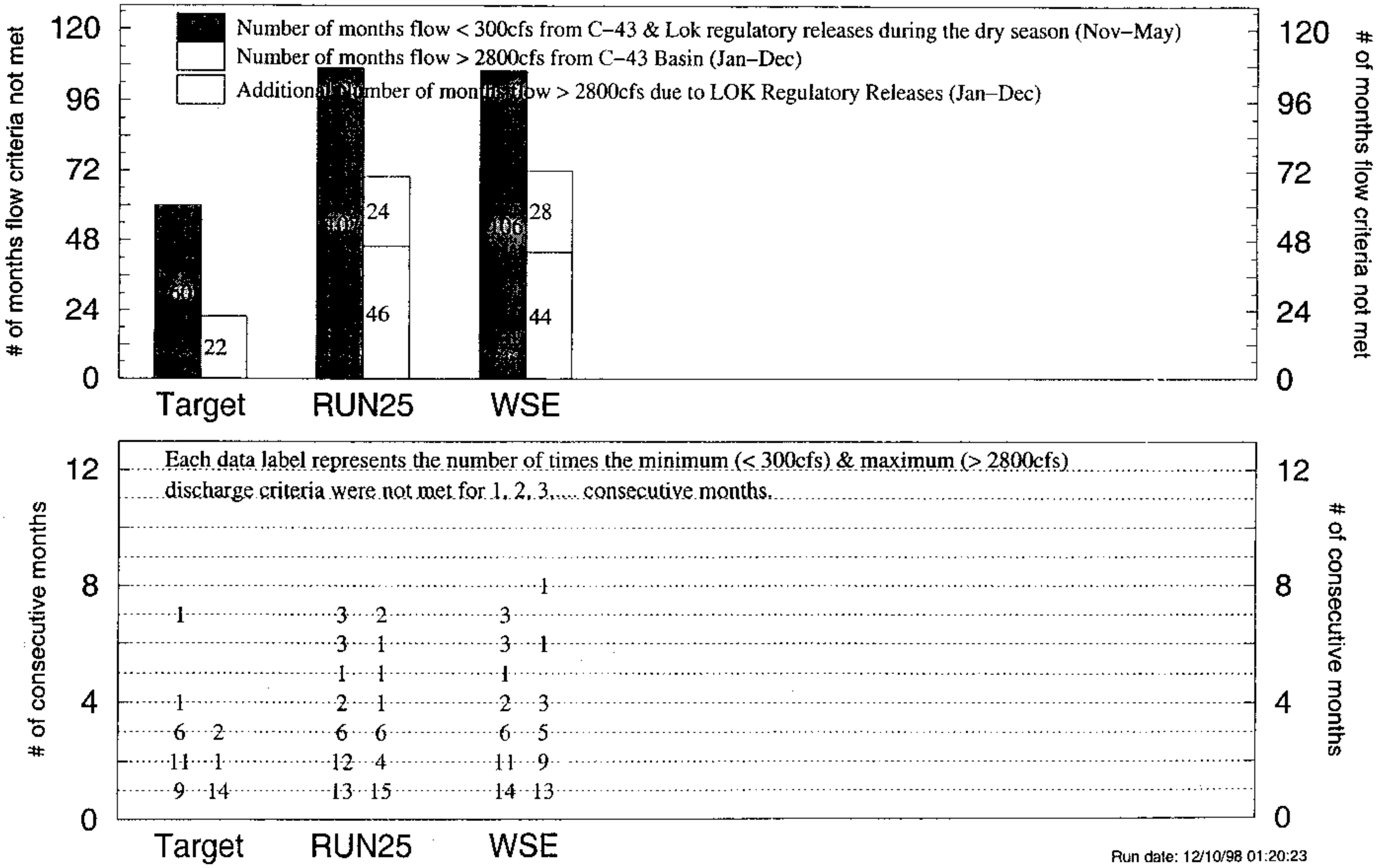
SFWMM V3.6P

Number of times Salinity Envelope Criteria were NOT met for the Caloosahatchee Estuary (mean monthly flows 1965 – 1995)



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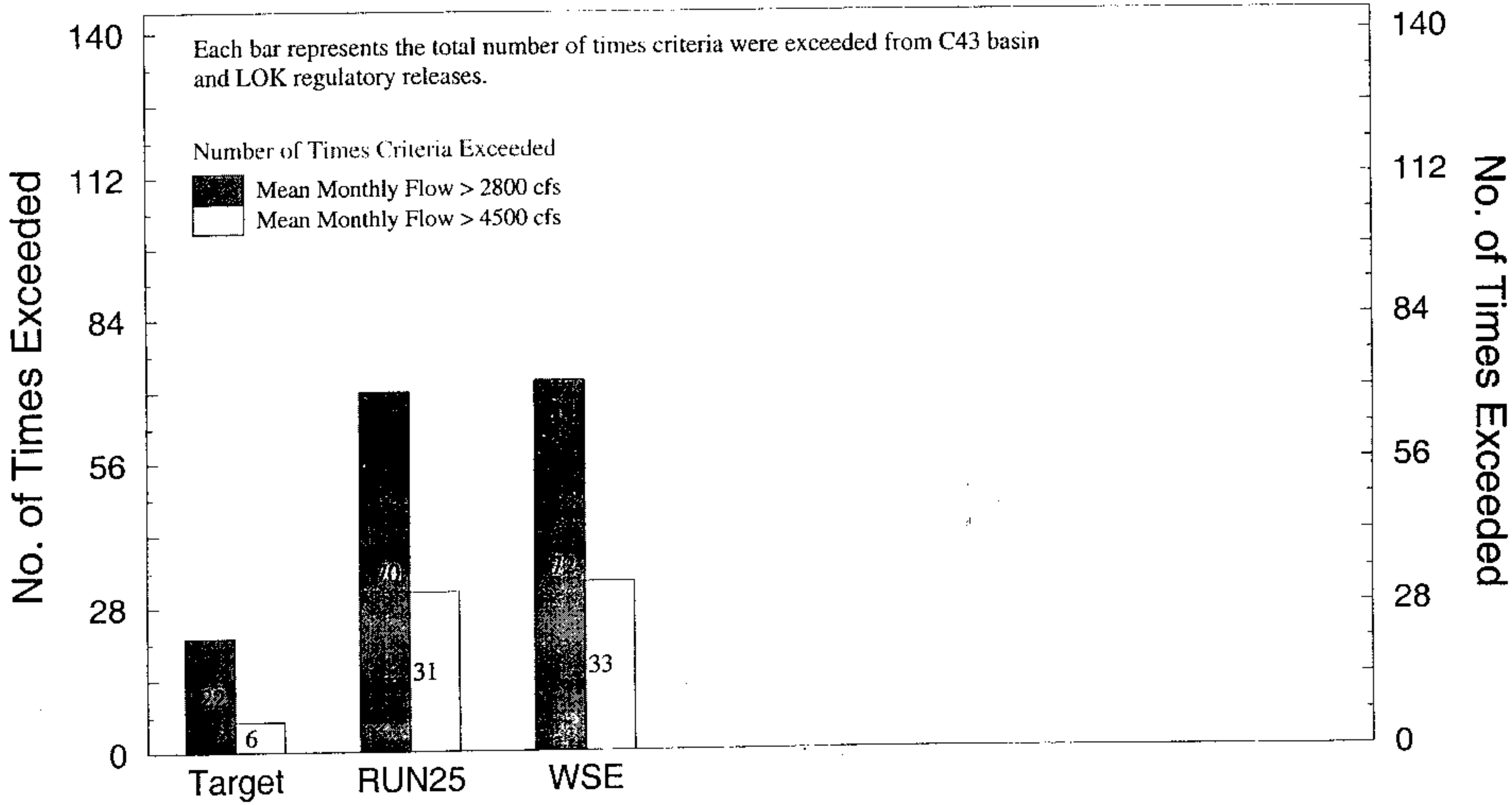
SFWMM V3.6P

Number of Times High Discharge Criteria (mean monthly flows > 2800 & 4500 cfs) were exceeded for the Caloosahatchee Estuary



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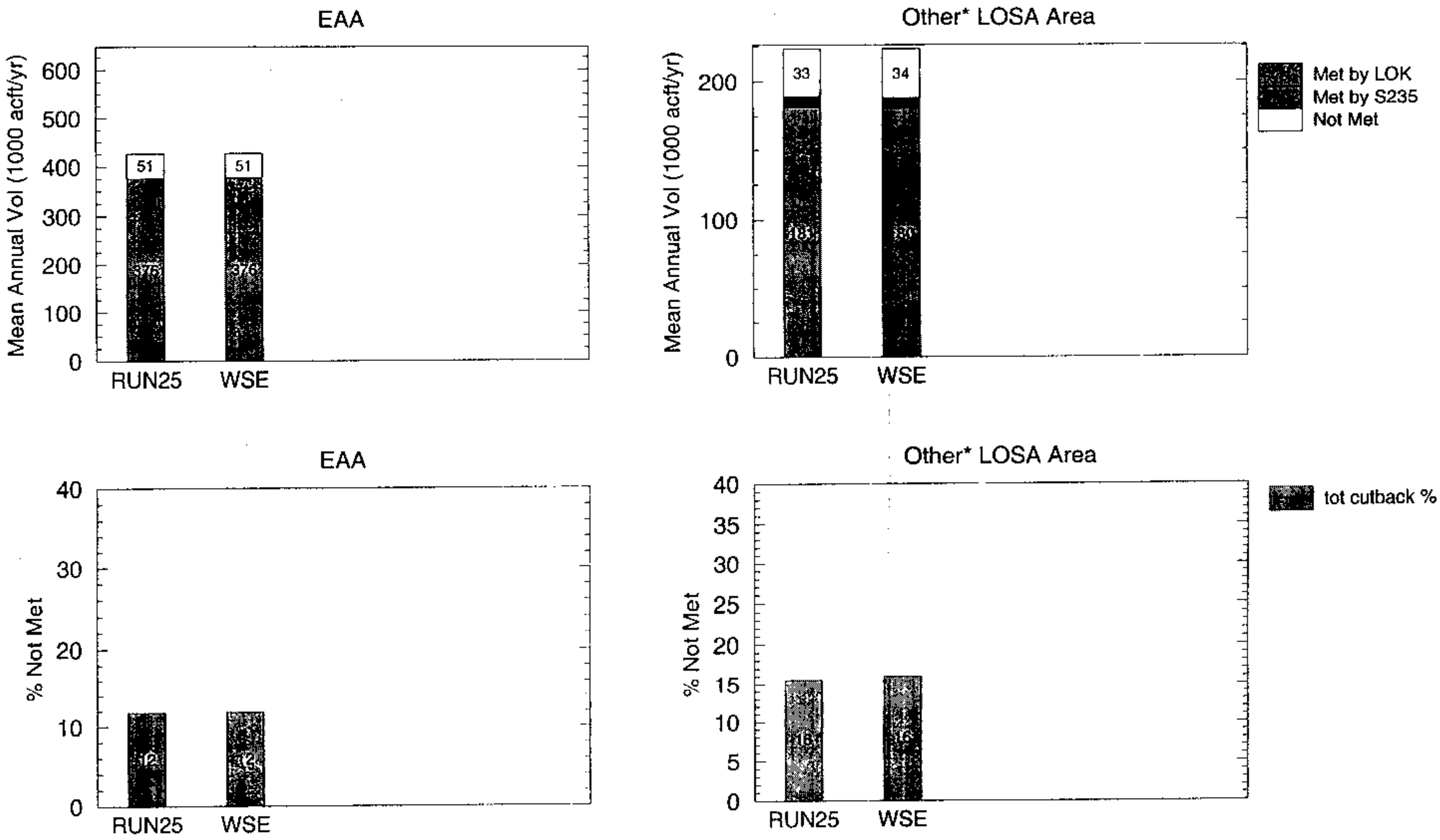
For Planning Purposes Only
SFWMM V3.6P

Performance Measures for the
Lake Okeechobee Service Area

Mean Annual EAA/LOSA Supplemental Irrigation: Demands and Demands Not Met

for the 1965 – 1995 Simulation Period



*Other Lake Service SubAreas (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

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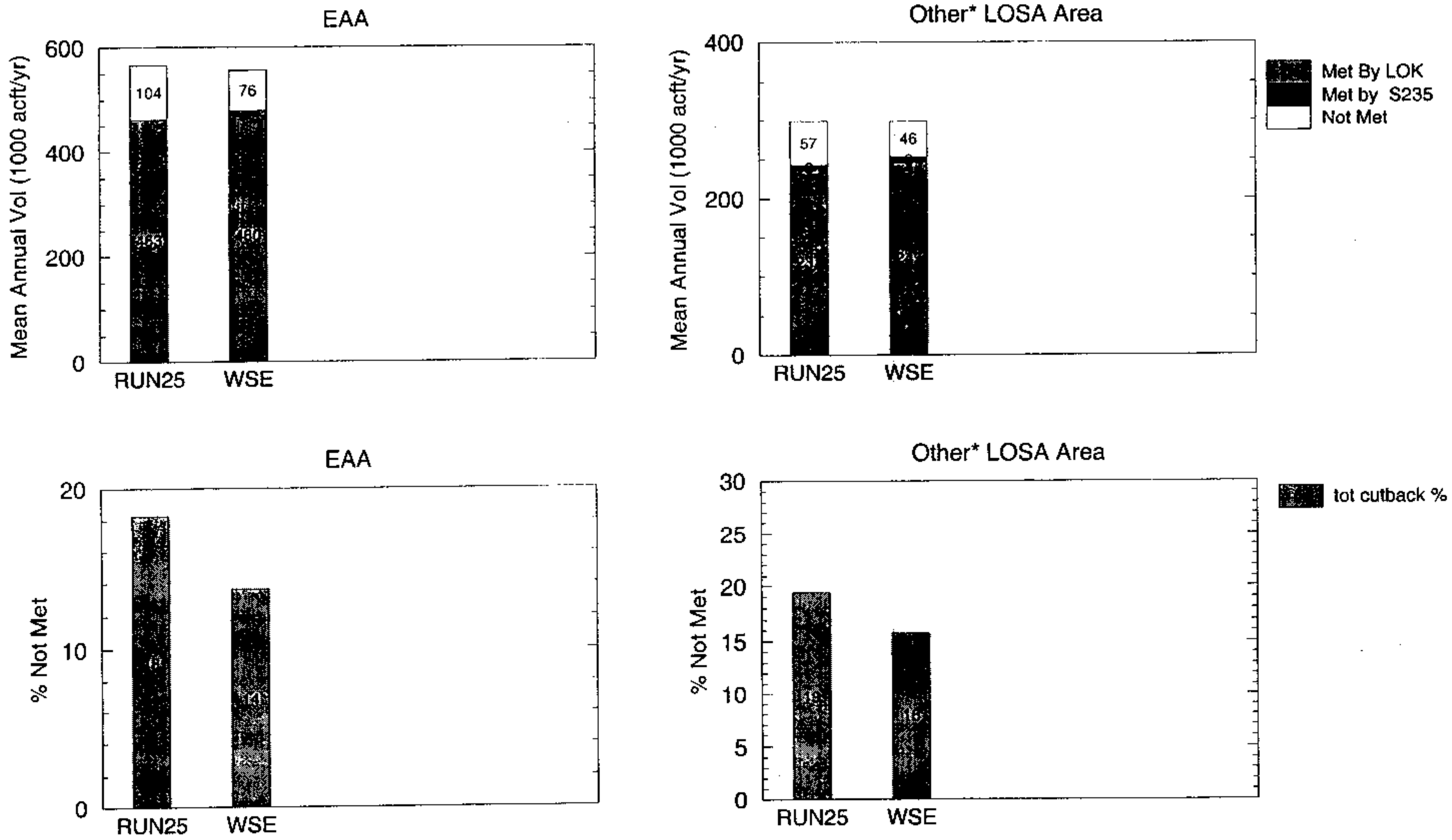
For Planning Purposes Only
SFWMM V3.6P

Mean Annual EAA/LOSA Supplemental Irrigation: Demands and Demands Not Met for the Drought Years: 1971, 1975, 1981, 1985, 1989 within the 1965 – 1995 Simulation Period



*Other Lake Service SubAreas (S236, S4, L8, C43, C44, and Seminole Indians (Brighton & Big Cypress)).

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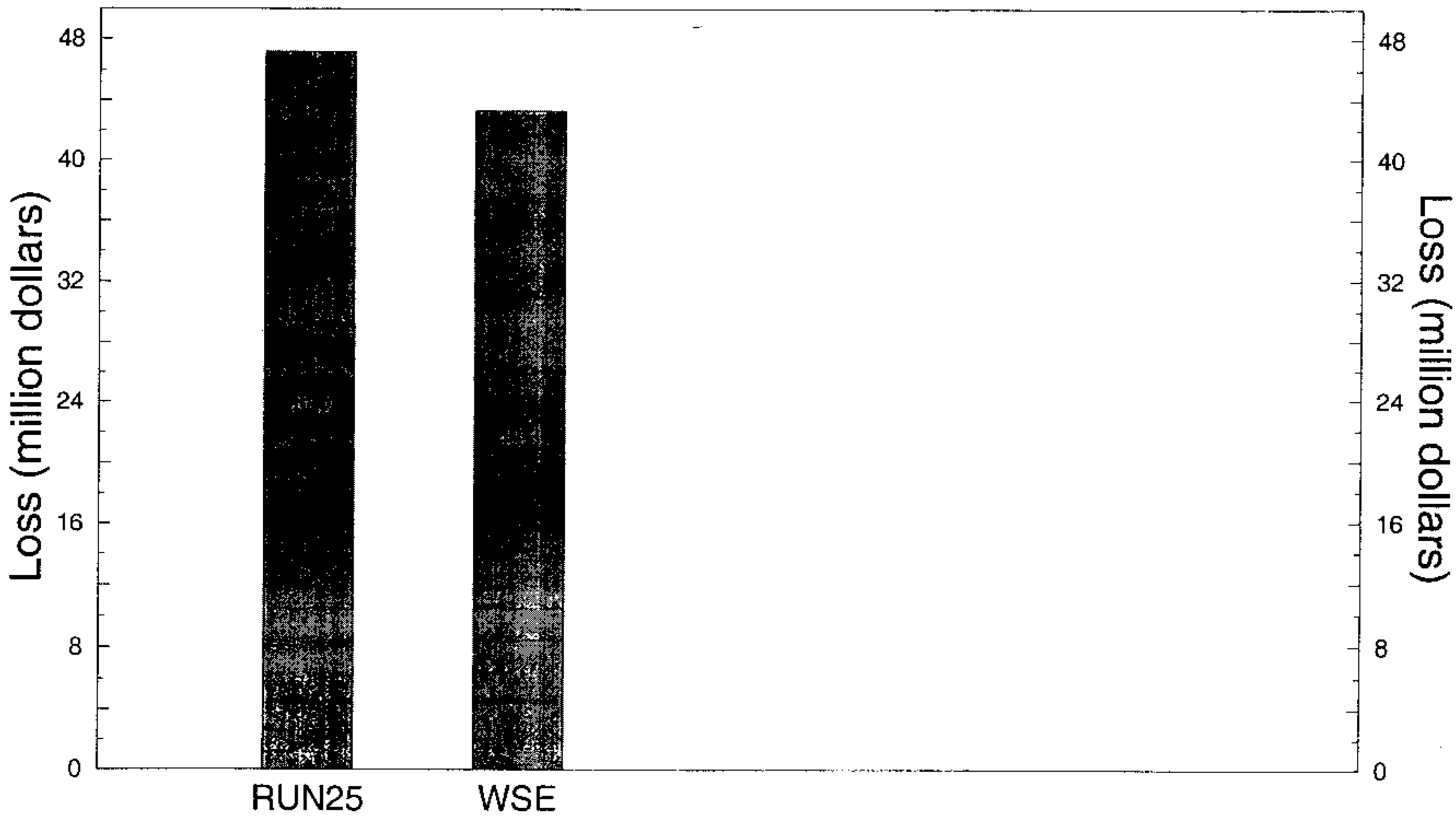
For Planning Purposes Only
SFWMM V3.6P

EAA IRRIGATED AREA ECONOMIC LOSSES
Total Losses Due to ET Reduction for 26 yr. simulation

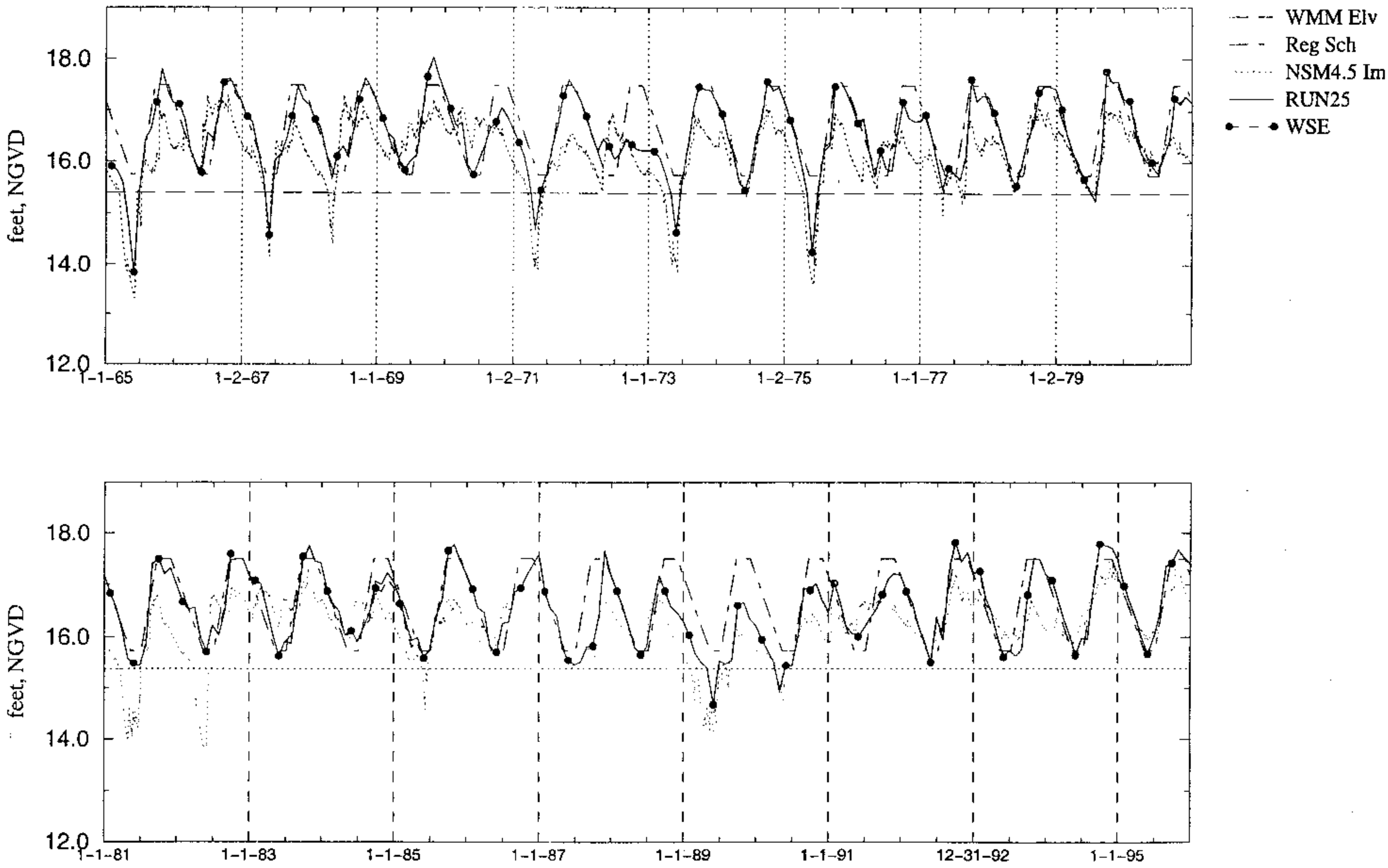


Note: Losses are based on Yield Reductions for Sugarcane in the EAA.
Sugarcane acreage(acres): 529,920(1990) 491,520(2010)

Run date: 12/10/98 02:22:36
For Planning Purposes Only
SFWMM V3.6P

Performance Measures for the
Everglades WCAs

Import Stage Hydrograph for WCA-1
Gage 1-7 Cell R48 C31



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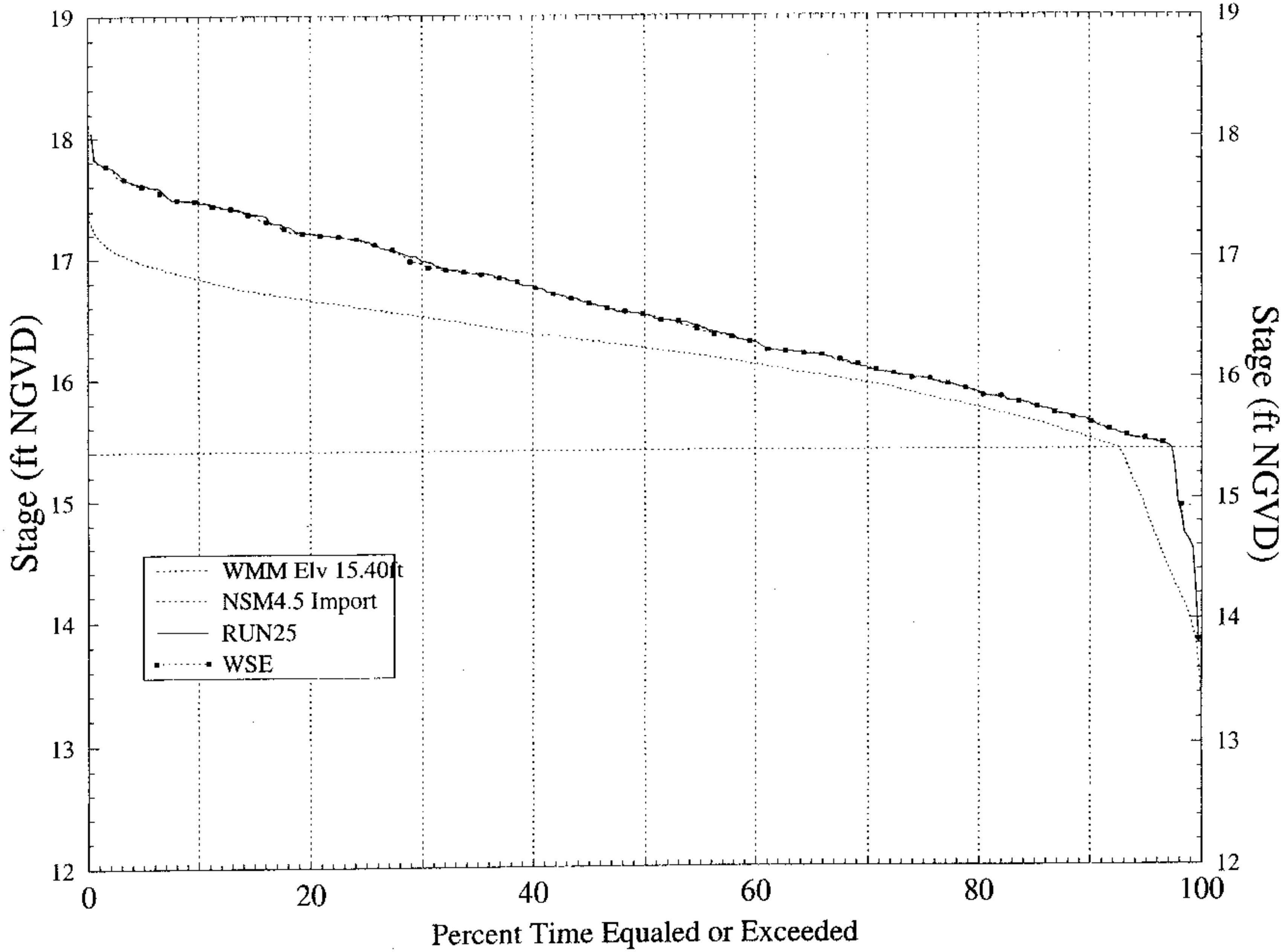
For Planning Purposes Only
SFWMM V3.6P

Import Stg Duration Curves for WCA−1
Gage 1−7 Cell R48 C31



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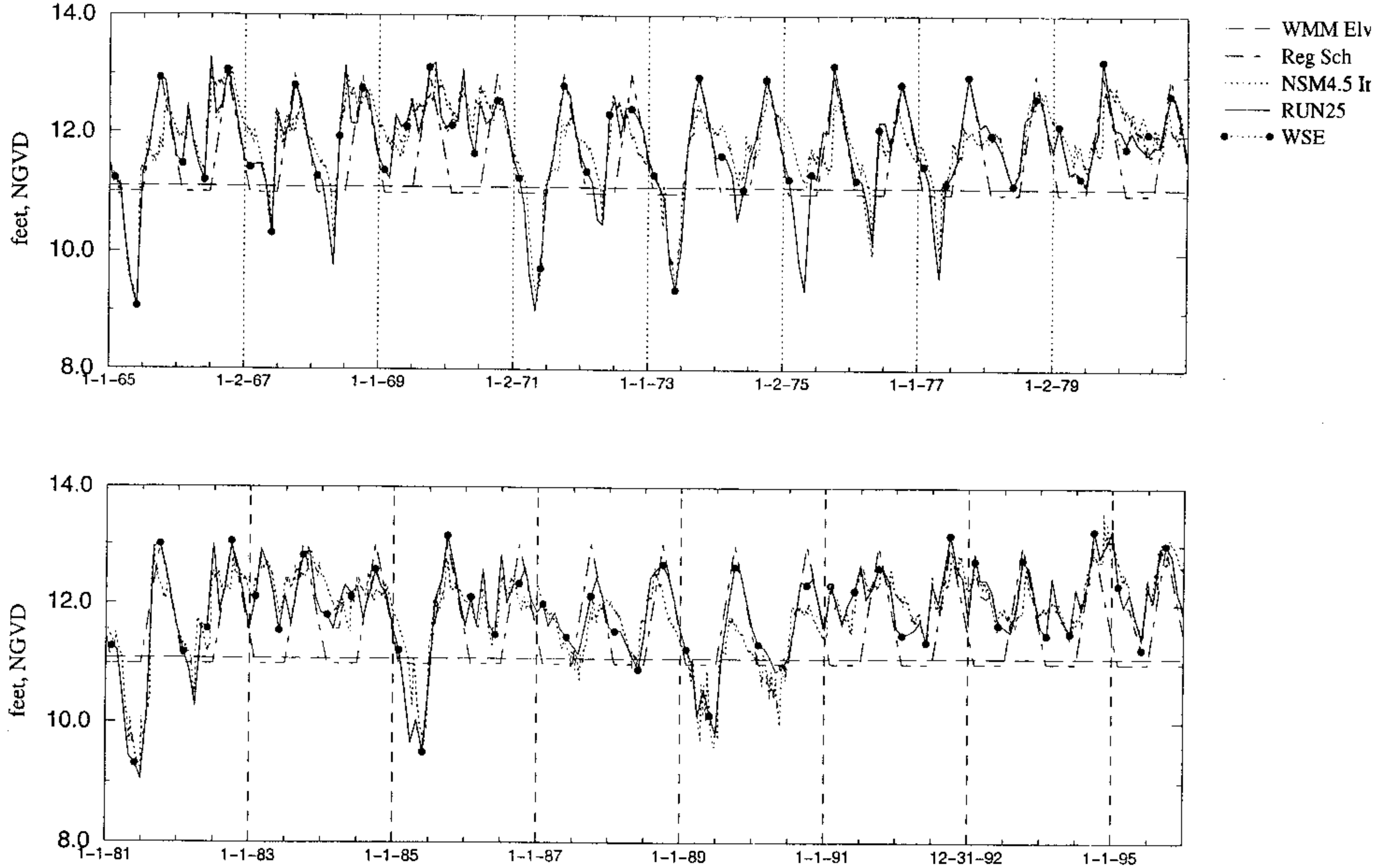
For Planning Purposes Only
SFWMM V3.6P

Import Stage Hydrograph for WCA-2A
Gage 2-17 Cell R40 C29



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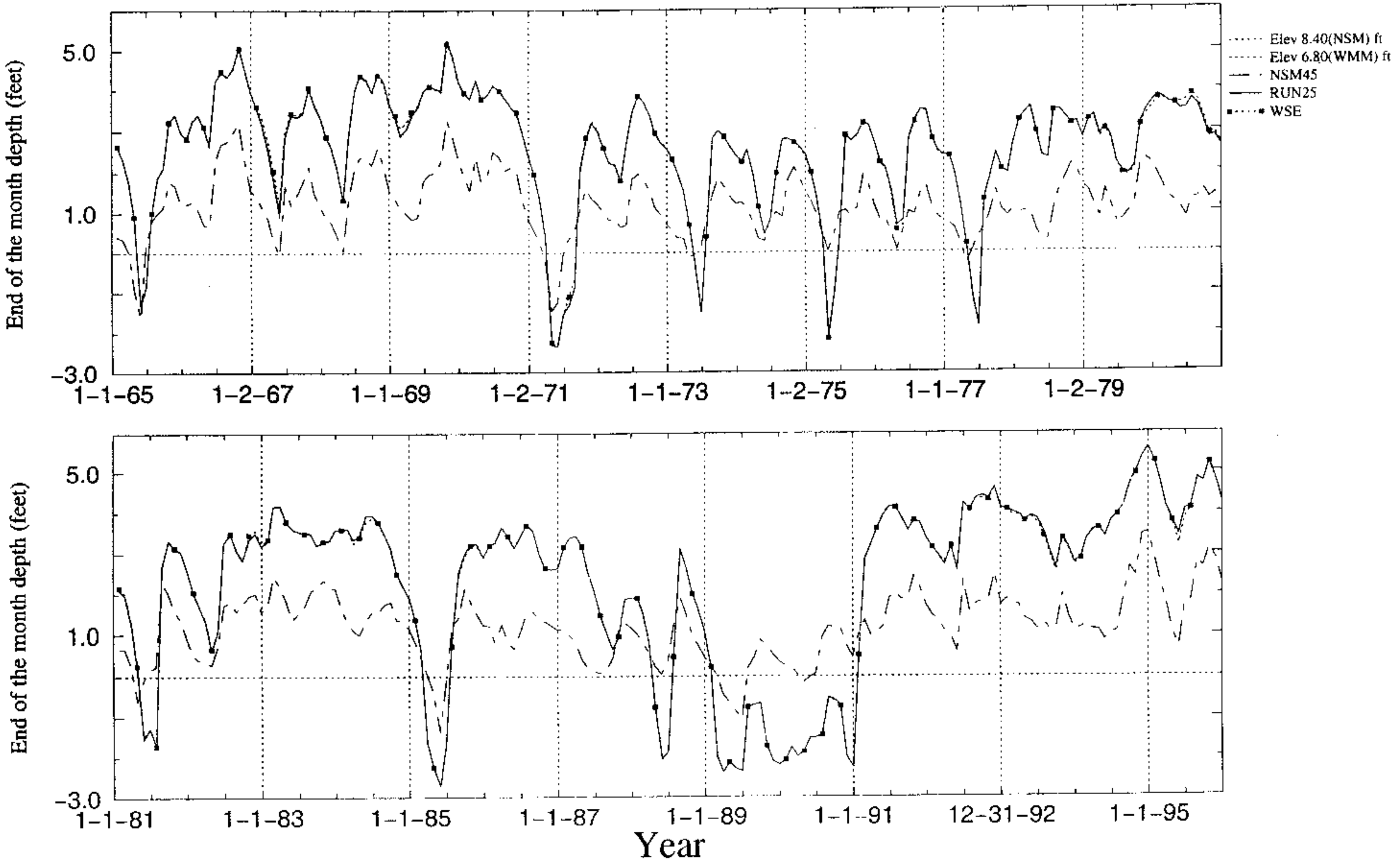
For Planning Purposes Only
SFWMM V3.6P

Normalized Stage Hydrograph at Cell (R35 C30)
South End of WCA–2B (Gage 2B–21)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table

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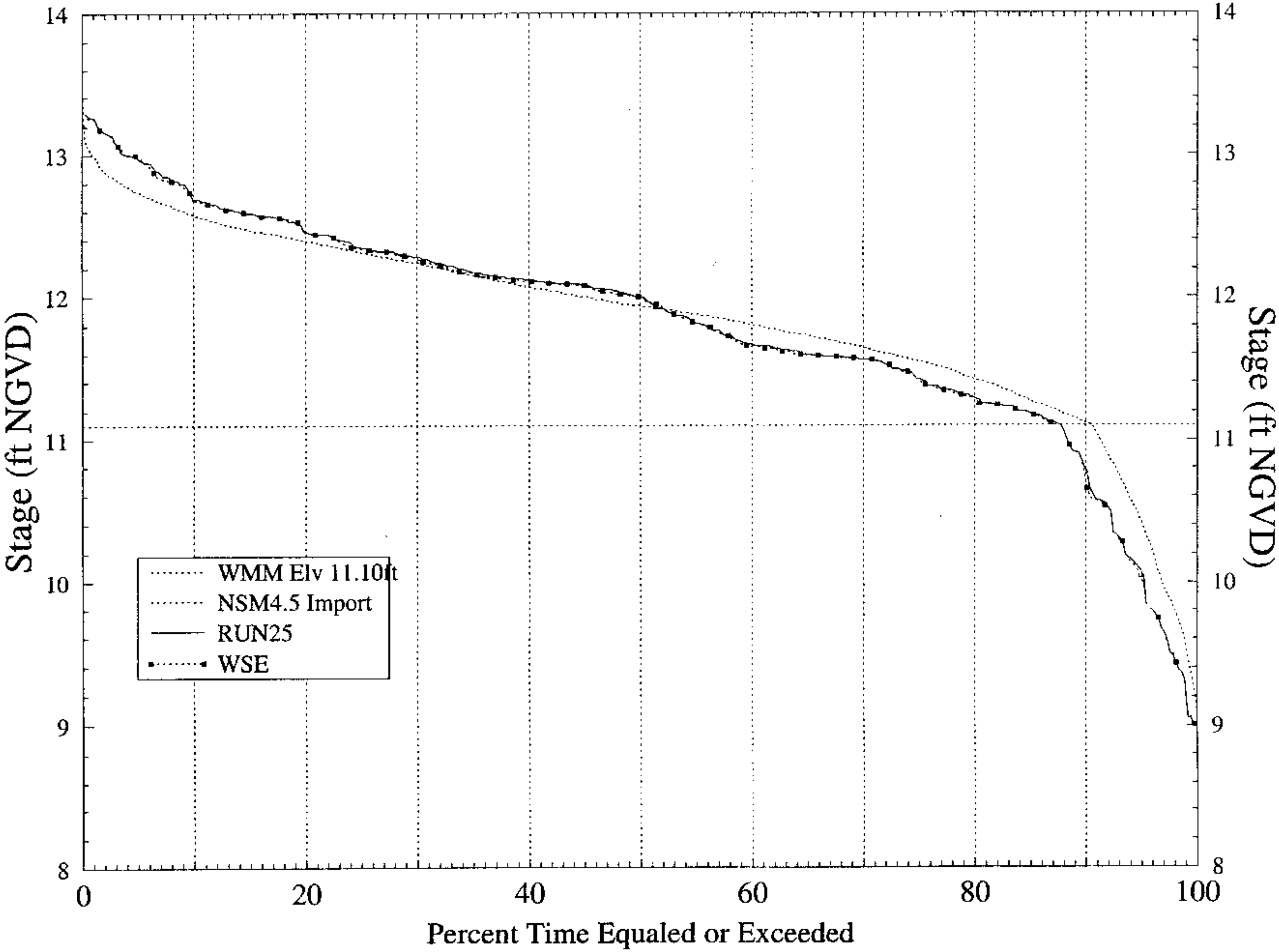
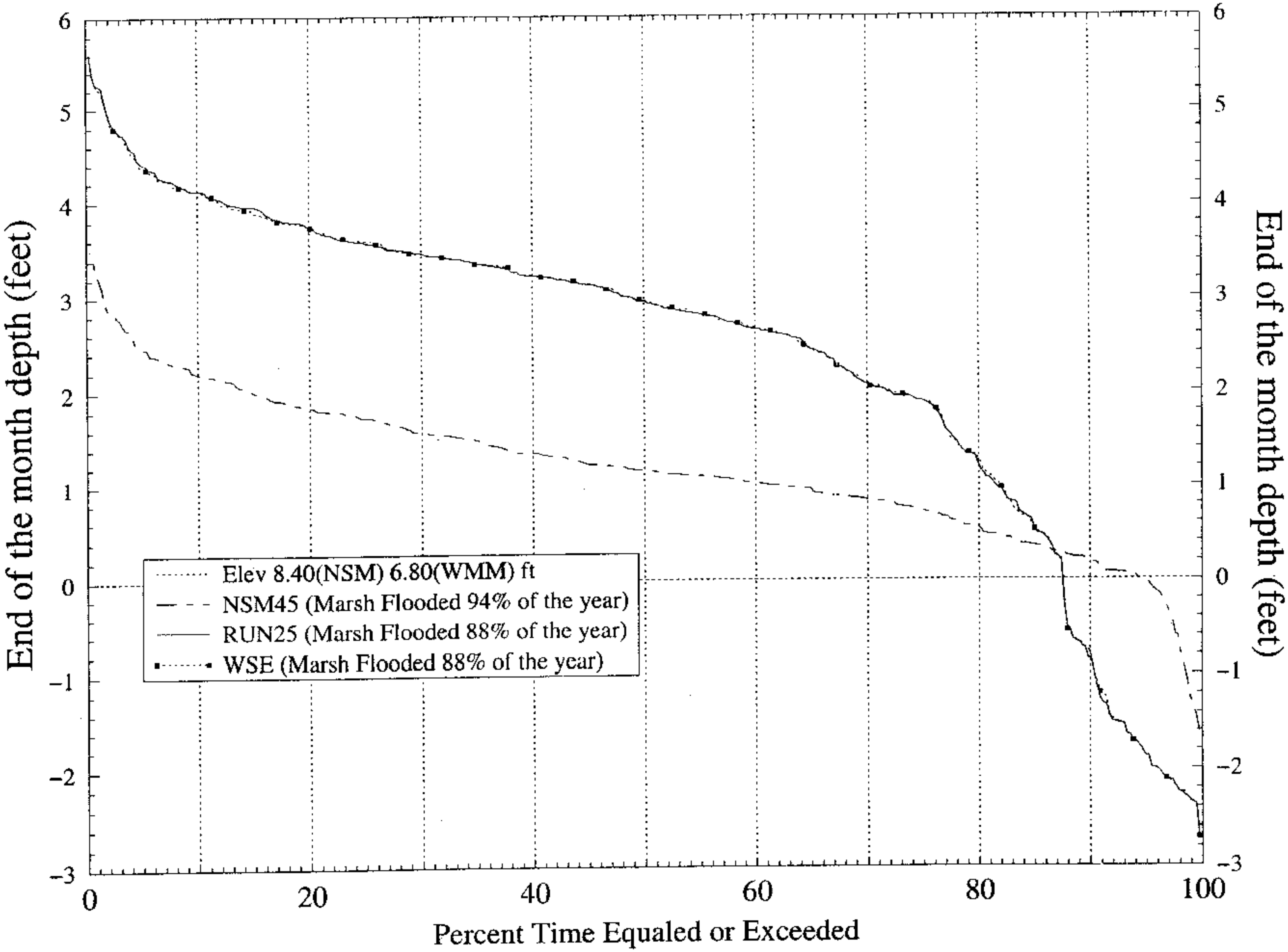
For Planning Purposes Only
SFWMM V3.6P

Import Stg Duration Curves for WCA–2A
Gage 2–17 Cell R40 C29



Run date: 12/10/98 02:28:24
For Planning Purposes Only
SFWMM V3.6P

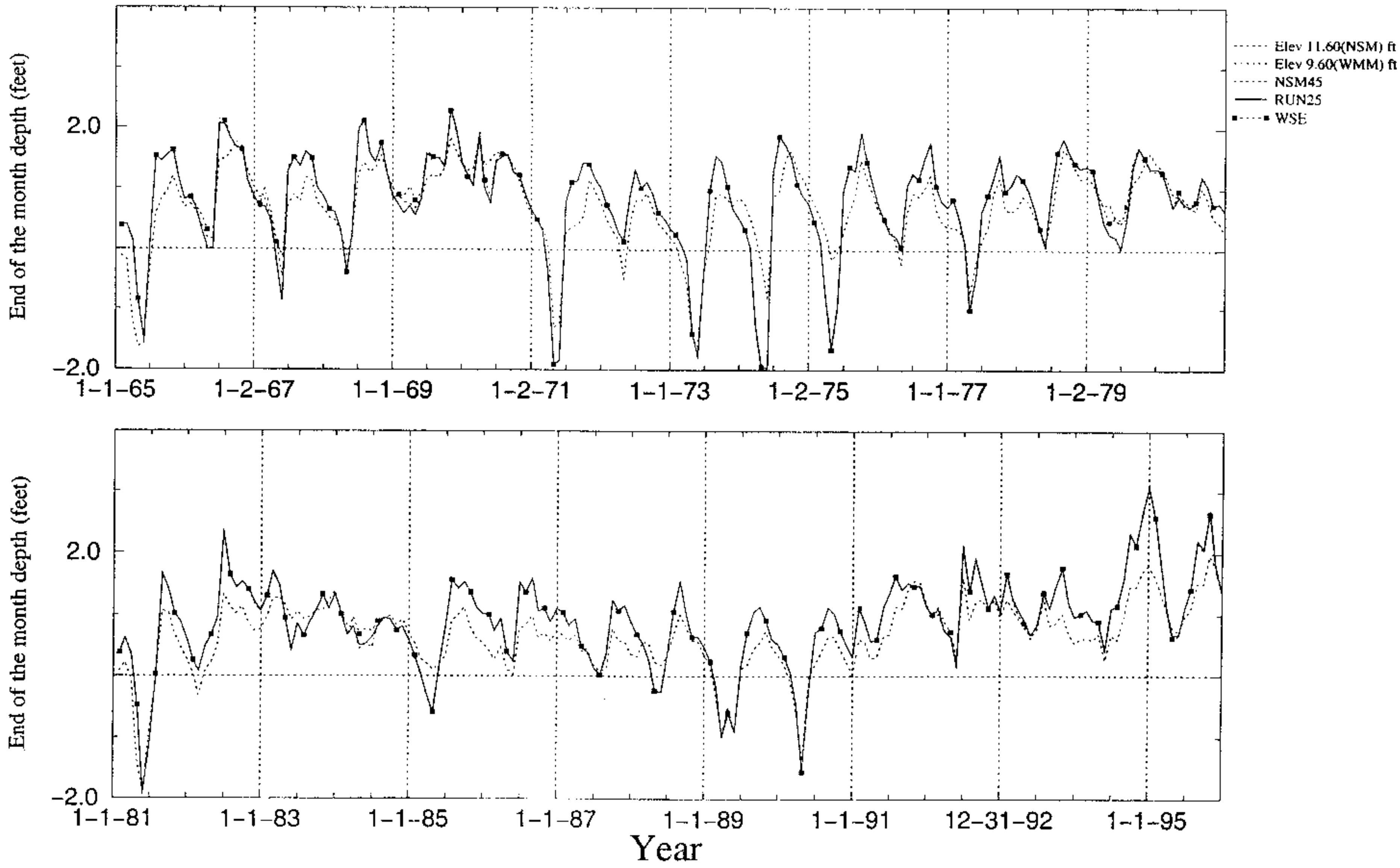
Normalized Stage Duration Curves at Cell (R35 C30)
South End of WCA-2B (Gage 2B-21)



Run date: 12/10/98 03:01:52
For Planning Purposes Only
SFWMM V3.6P

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

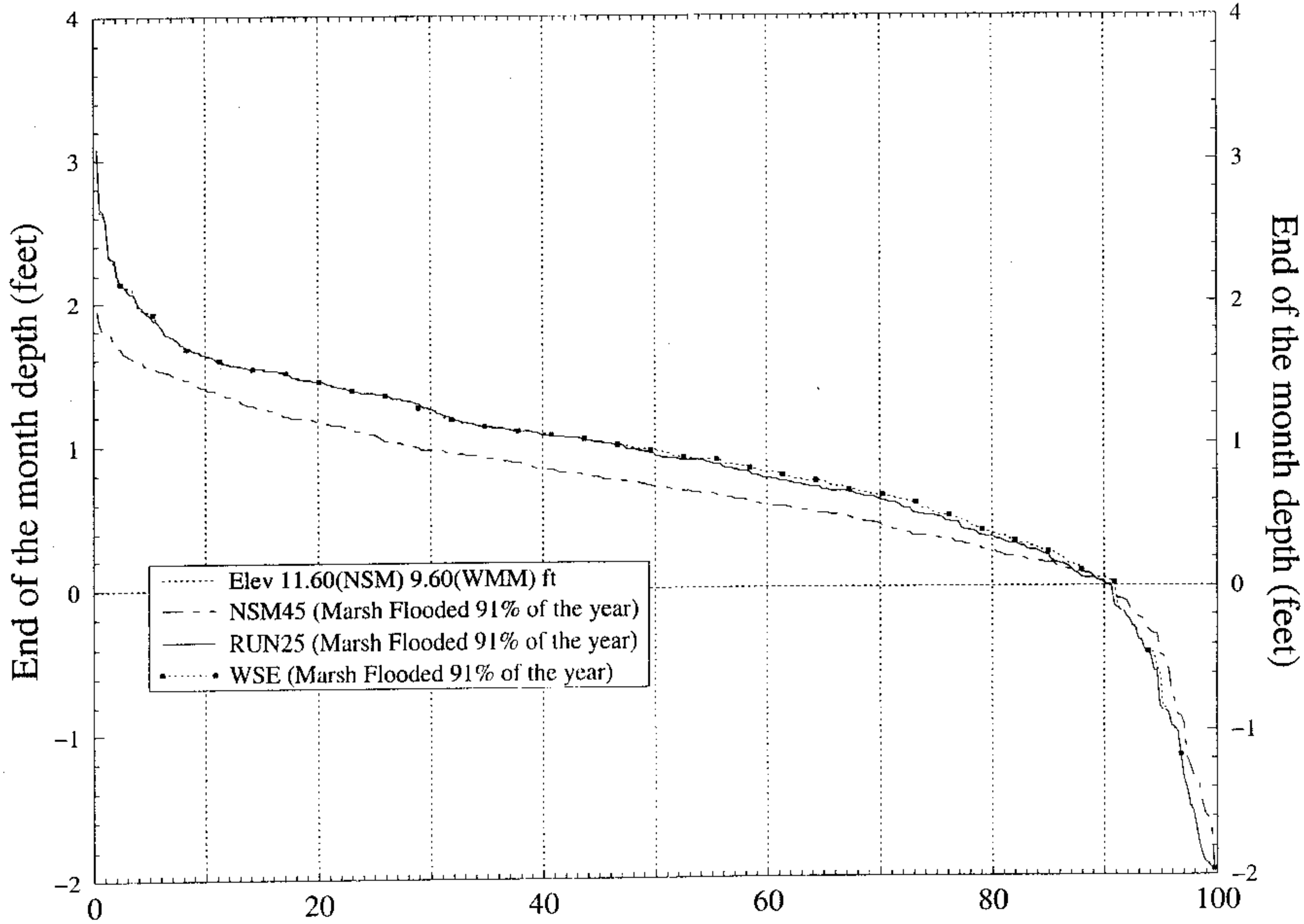
Normalized Stage Hydrograph at Cell (R36 C18)
North End of WCA–3A (Gage 3A–2)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 12/10/98 03:20:37
For Planning Purposes Only
SFWMM V3.6P

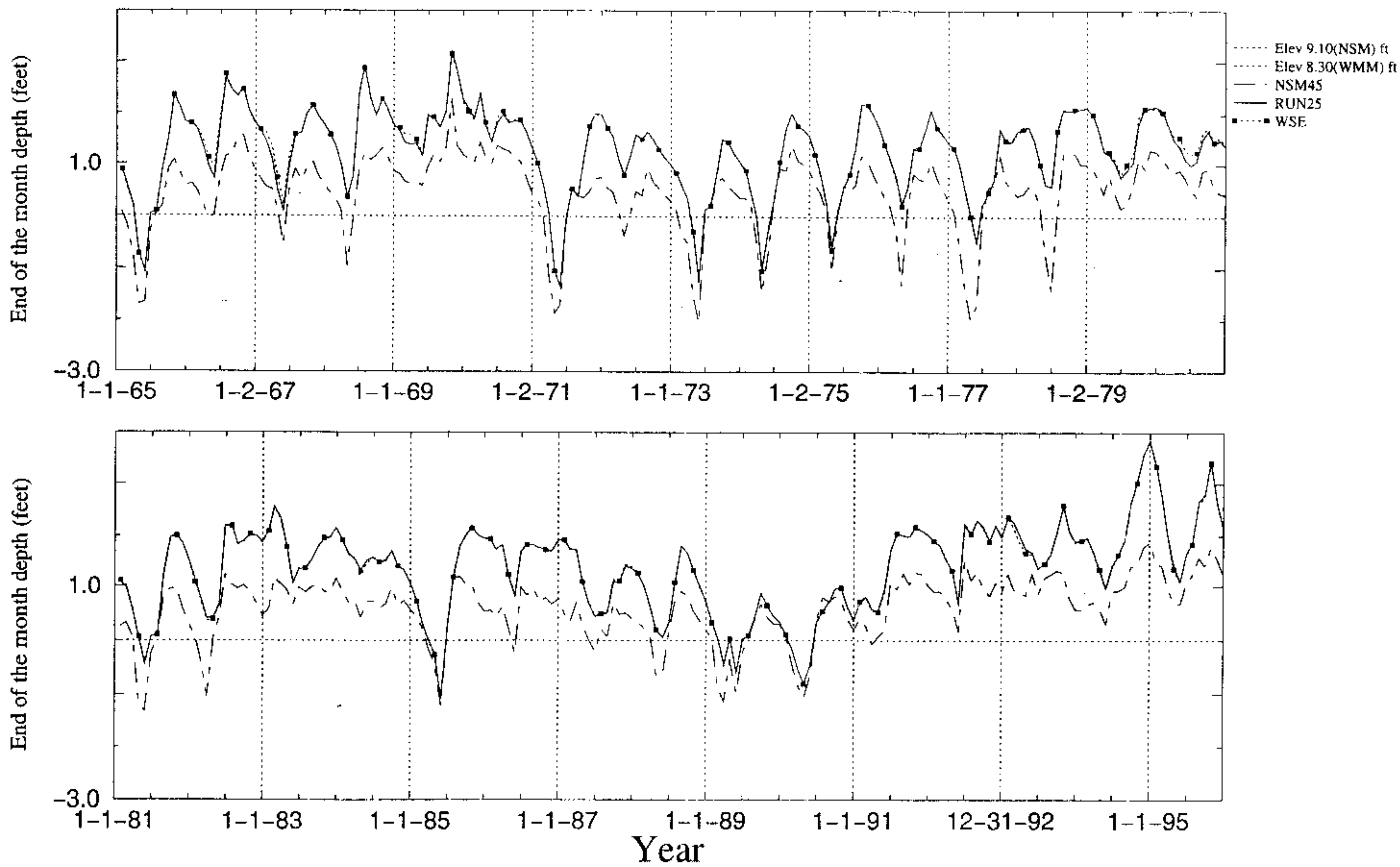
Normalized Stage Duration Curves at Cell (R36 C18)
North End of WCA–3A (Gage 3A–2)



Run date: 12/10/98 03:20:22
For Planning Purposes Only
SFWMM V3.6P

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

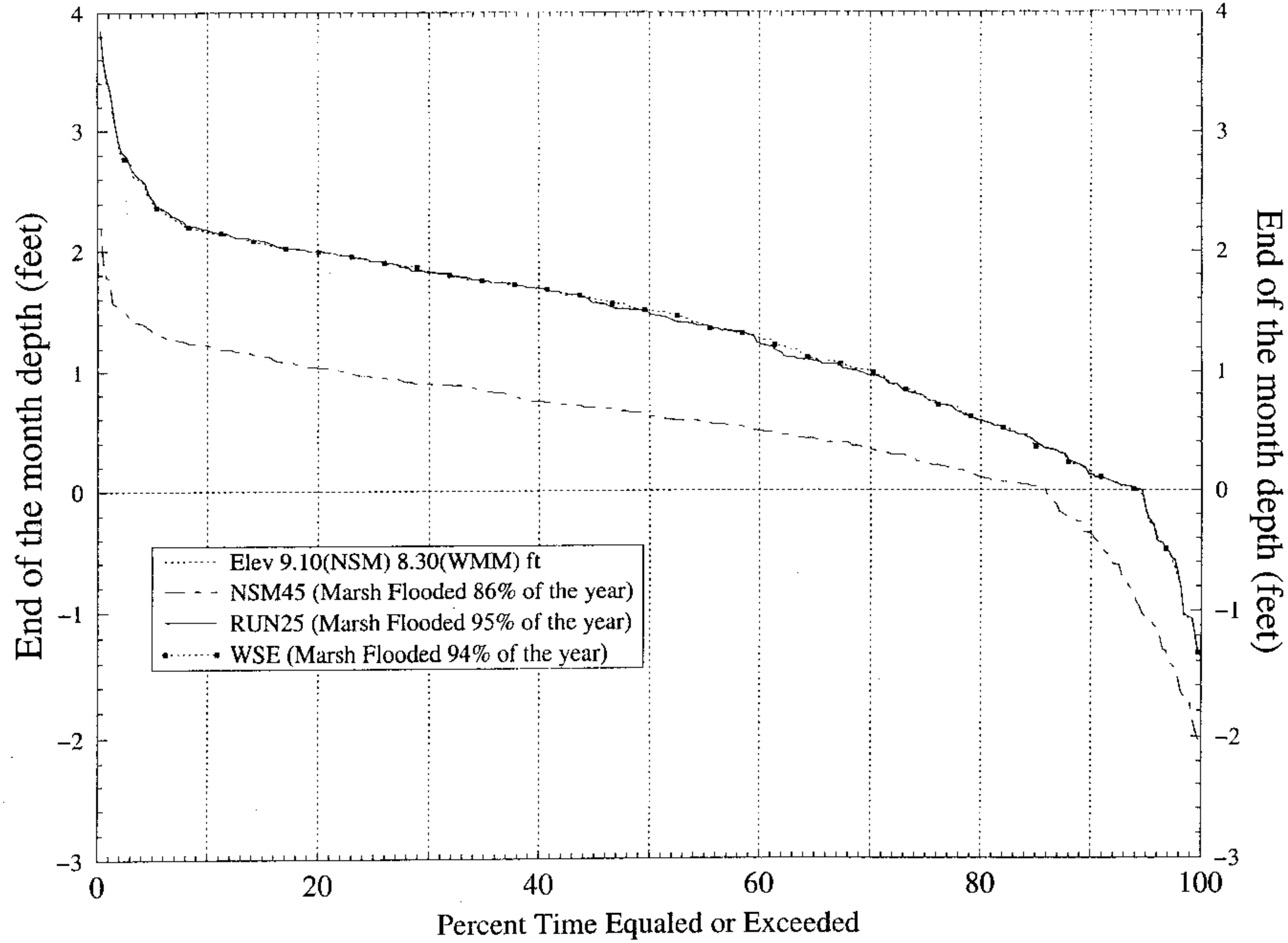
Normalized Stage Hydrograph at Cell (R29 C21)
Central Portion of WCA−3A(Gage 3A−4)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 12/10/98 03:21:15
For Planning Purposes Only
SFWMM V3.6P

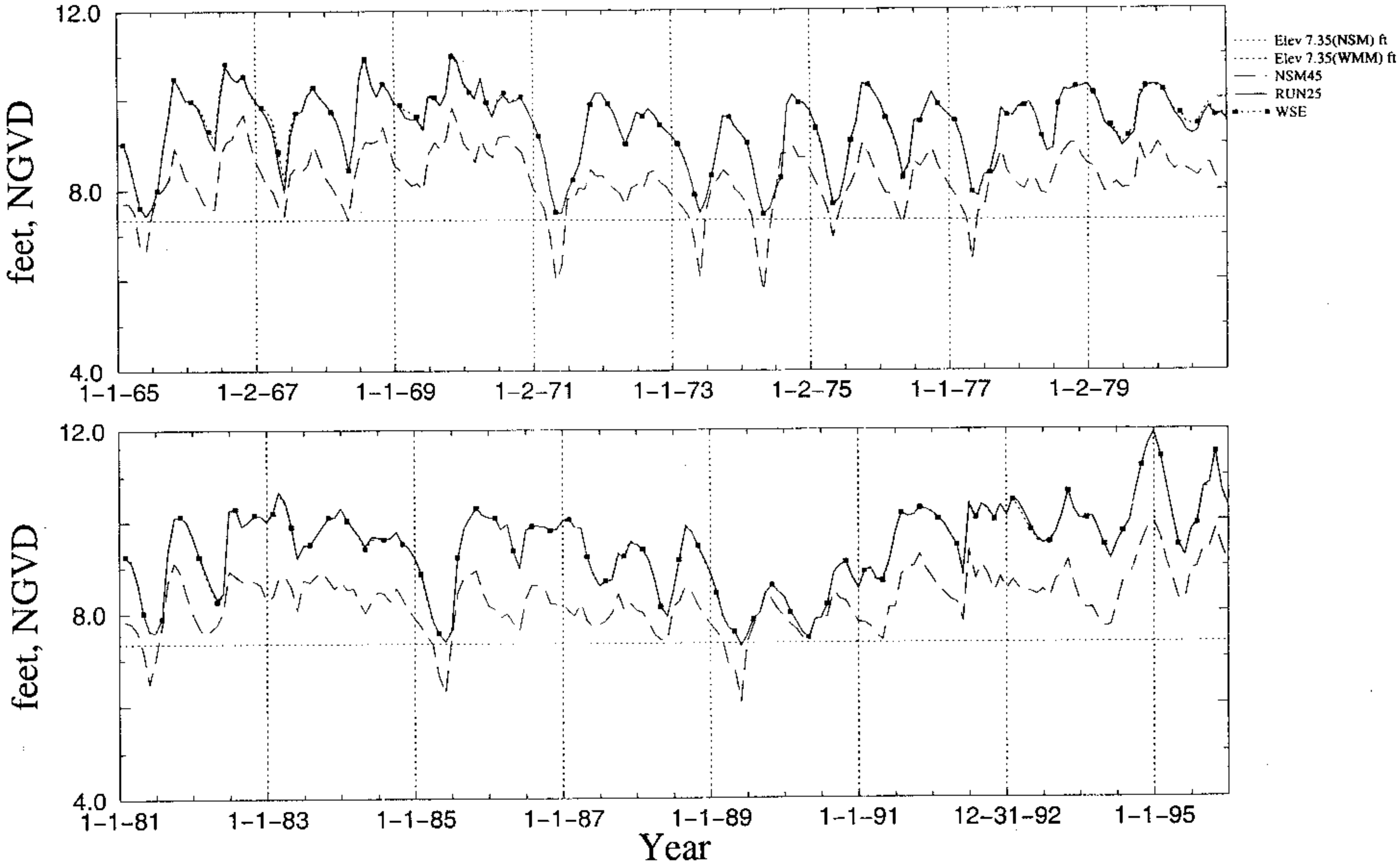
Normalized Stage Duration Curves at Cell (R29 C21)
Central Portion of WCA-3A(Gage 3A-4)



Run date: 12/10/98 03:21:00
For Planning Purposes Only
SFWMM V3.6P

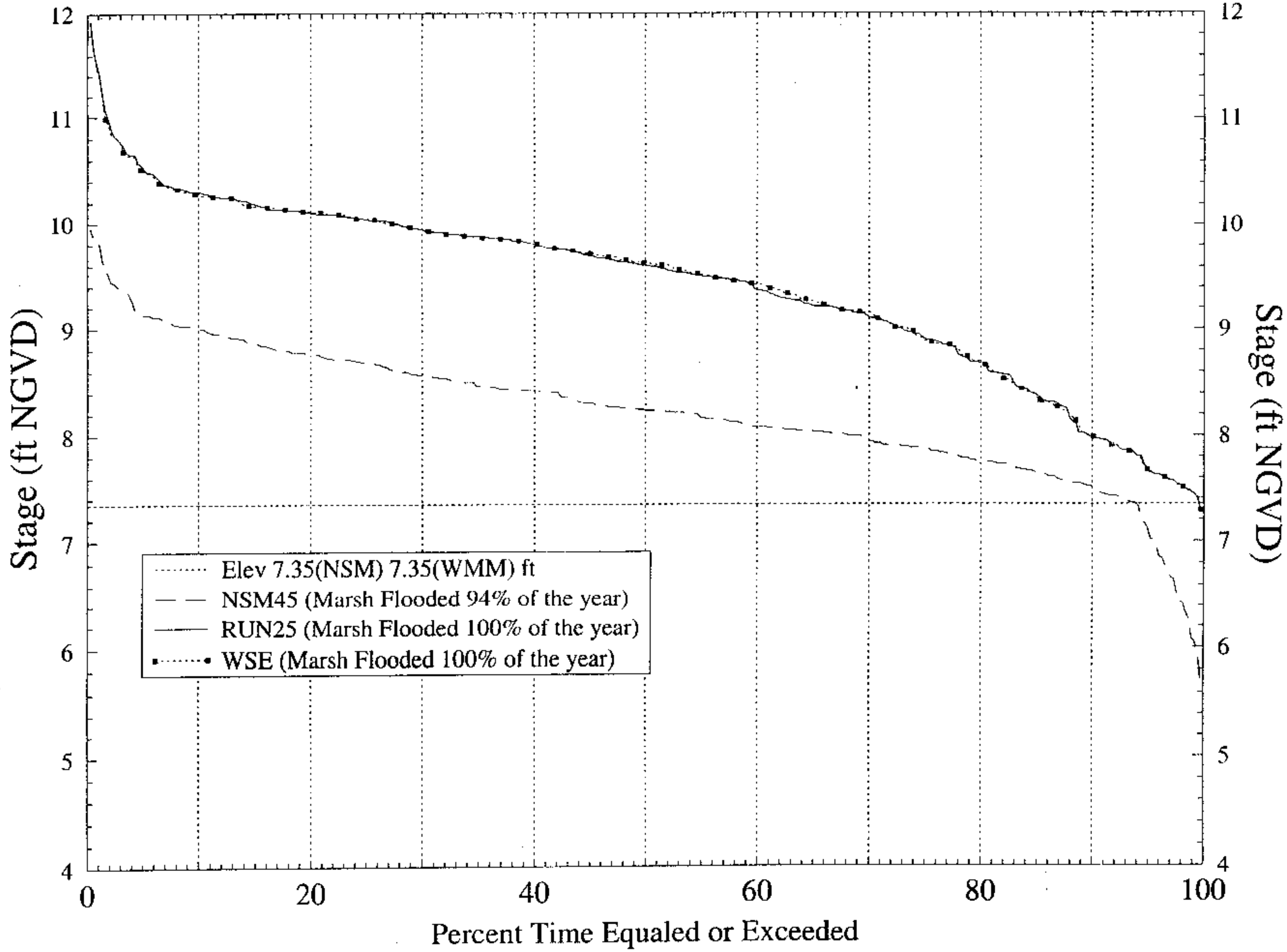
Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Stage Hydrograph for South End of WCA-3A
(Gage 3A-28, Cell R24 C19)



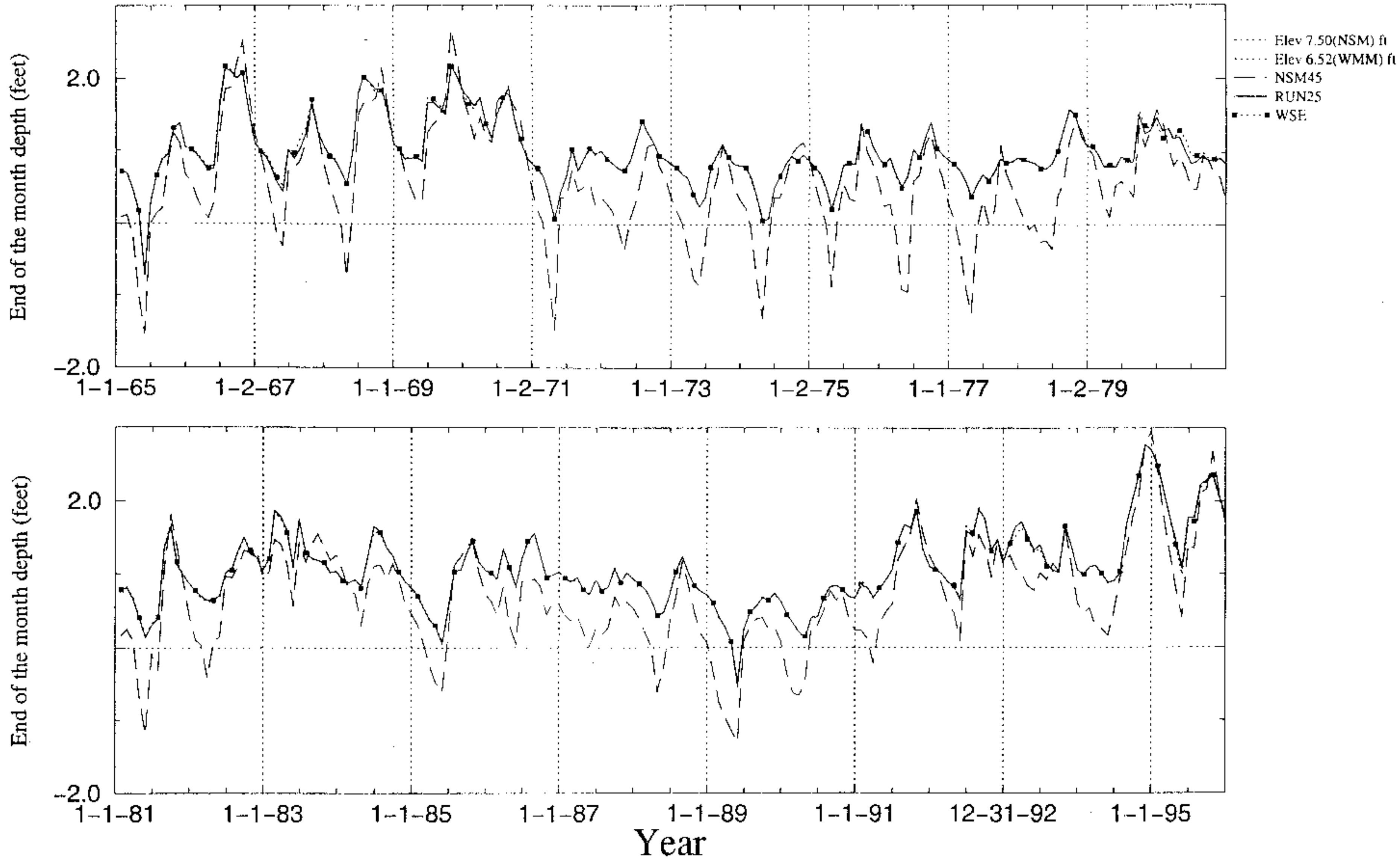
Run date: 12/10/98 02:51:03
For Planning Purposes Only
SFWMM V3.6P

Stage Duration Curves at South End of WCA–3A
(Gage 3A–28, Cell R24 C19)



Run date: 12/10/98 02:49:13
For Planning Purposes Only
SFWMM V3.6P

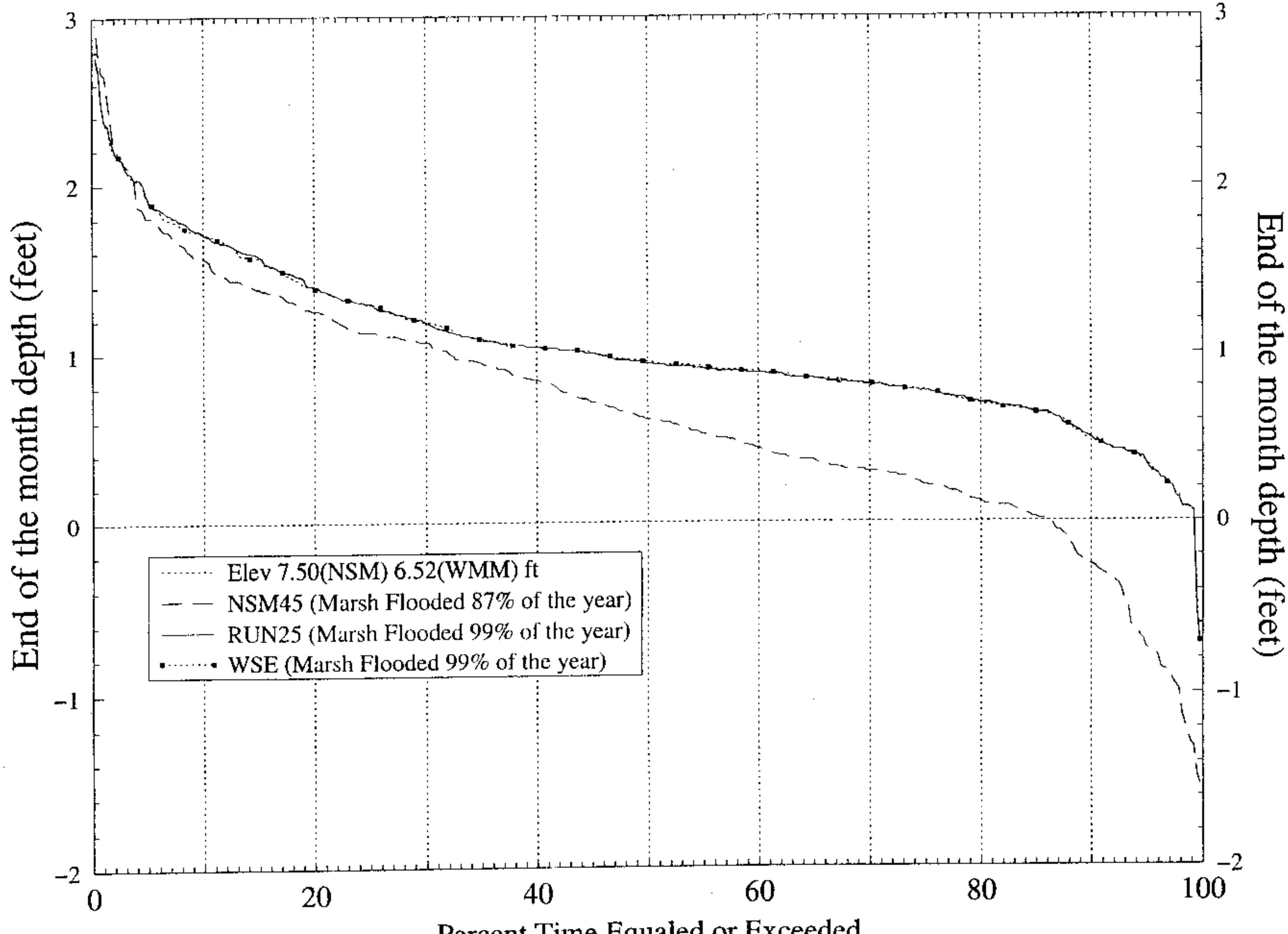
Normalized Stage Hydrograph at Cell (R26 C24)
West–Central WCA–3B (Gage 3B–2)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table

Run date: 12/10/98 03:23:52
For Planning Purposes Only
SFWMM V3.6P

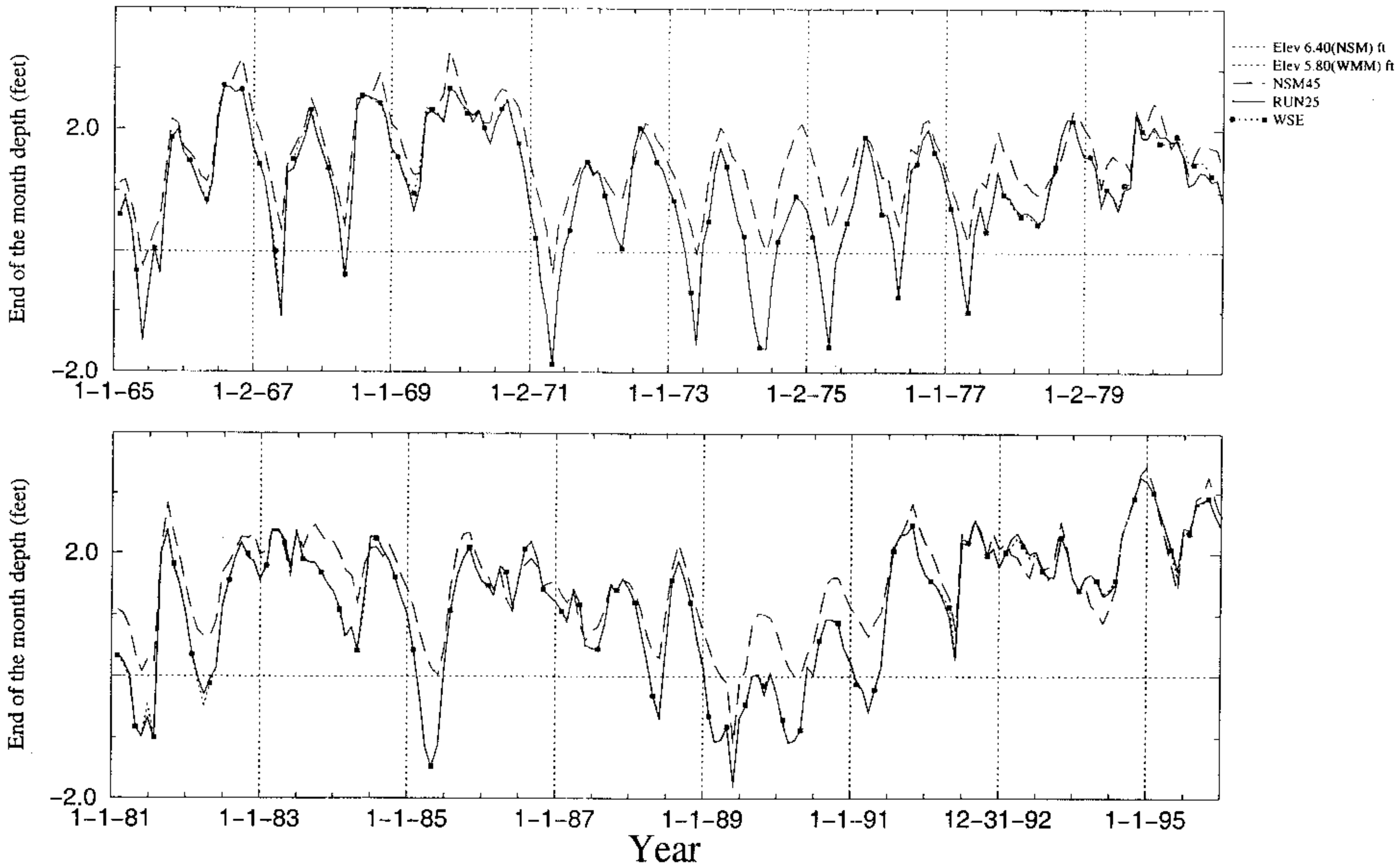
Normalized Stage Duration Curves at Cell (R26 C24)
West–Central WCA–3B (Gage 3B–2)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 12/10/98 03:23:36
For Planning Purposes Only
SFWMM V3.6P

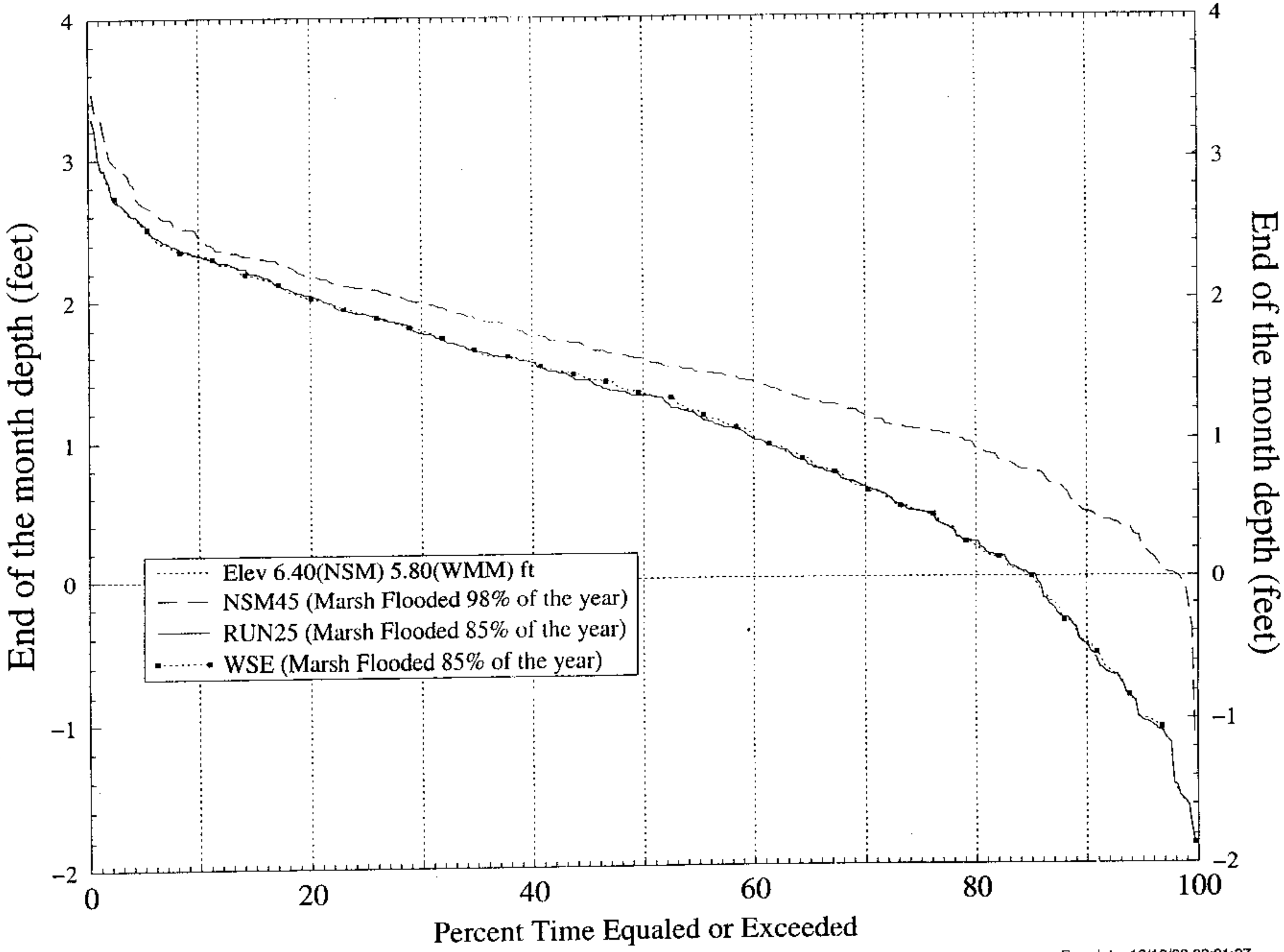
Normalized Stage Hydrograph at Cell (R23 C26)
South End of WCA–3B (Gage 3B–SE)



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 12/10/98 03:21:53
For Planning Purposes Only
SFWMM V3.6P

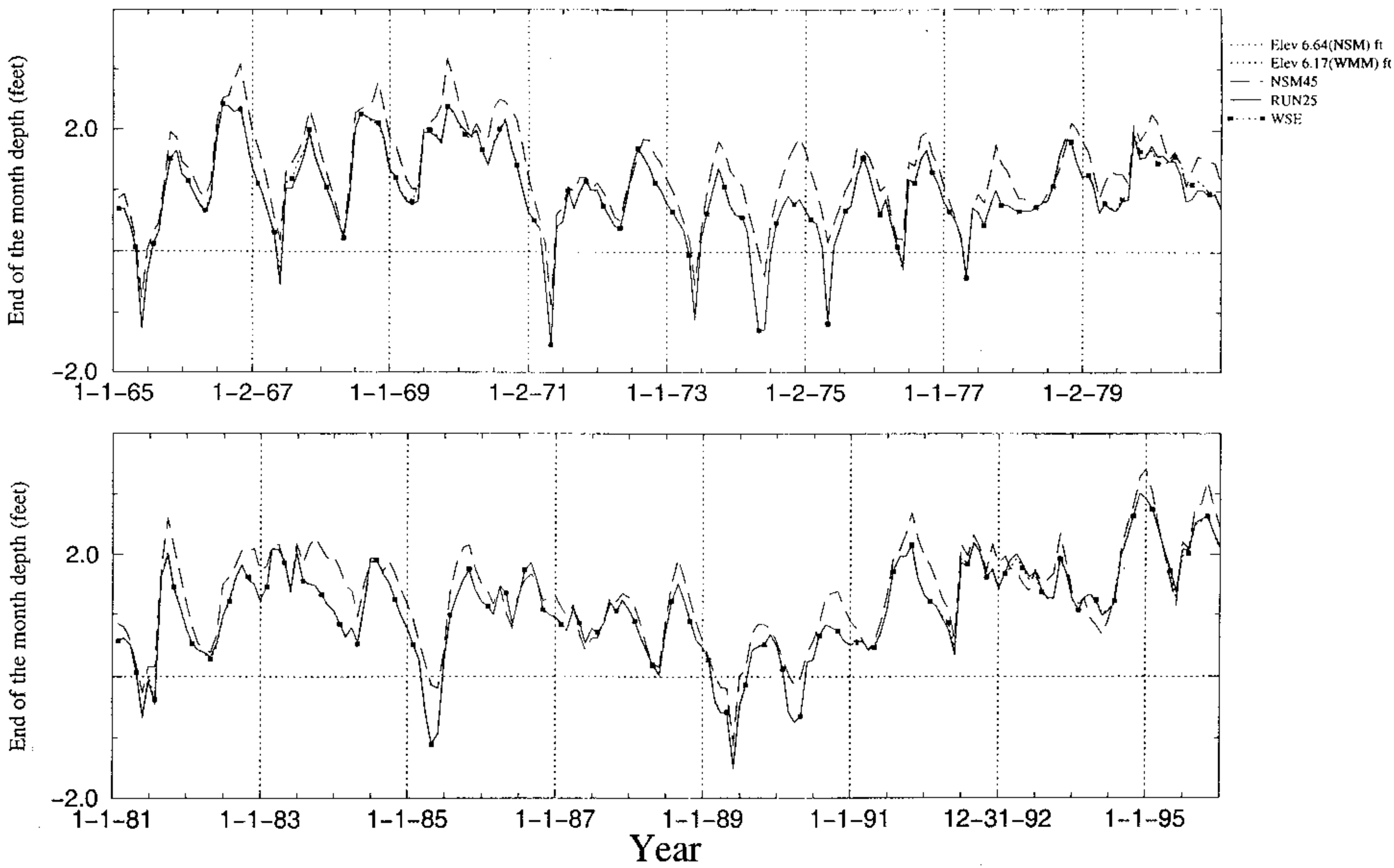
Normalized Stage Duration Curves at Cell (R23 C26)
South End of WCA-3B (Gage 3B-SE)



Run date: 12/10/98 03:21:37
For Planning Purposes Only
SFWMM V3.6P

Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding

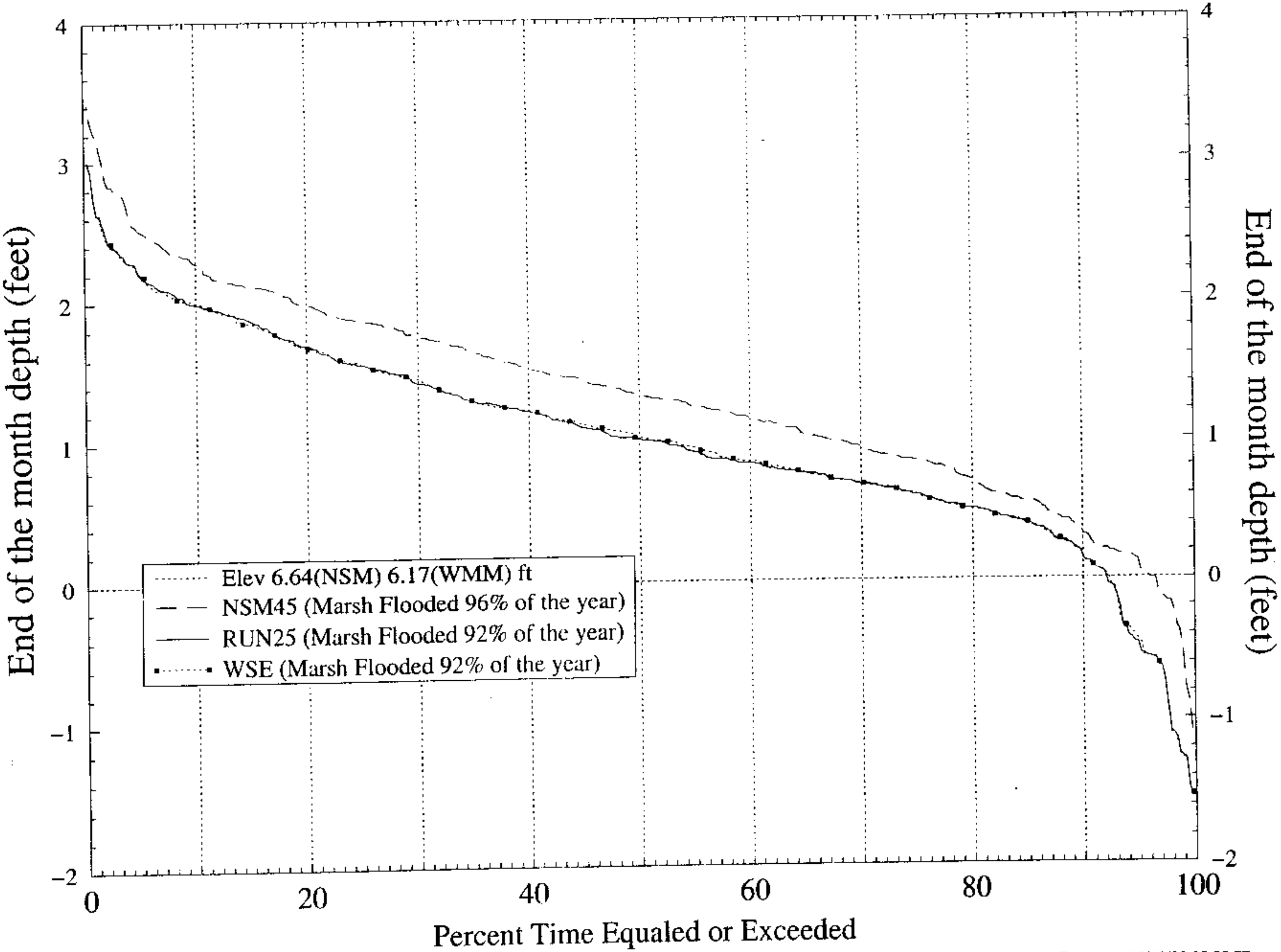
Normalized Stage Hydrograph at Cell (R24 C25)
South End of WCA–3B



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table

Run date: 12/10/98 03:23:12
For Planning Purposes Only
SFWMM V3.5P

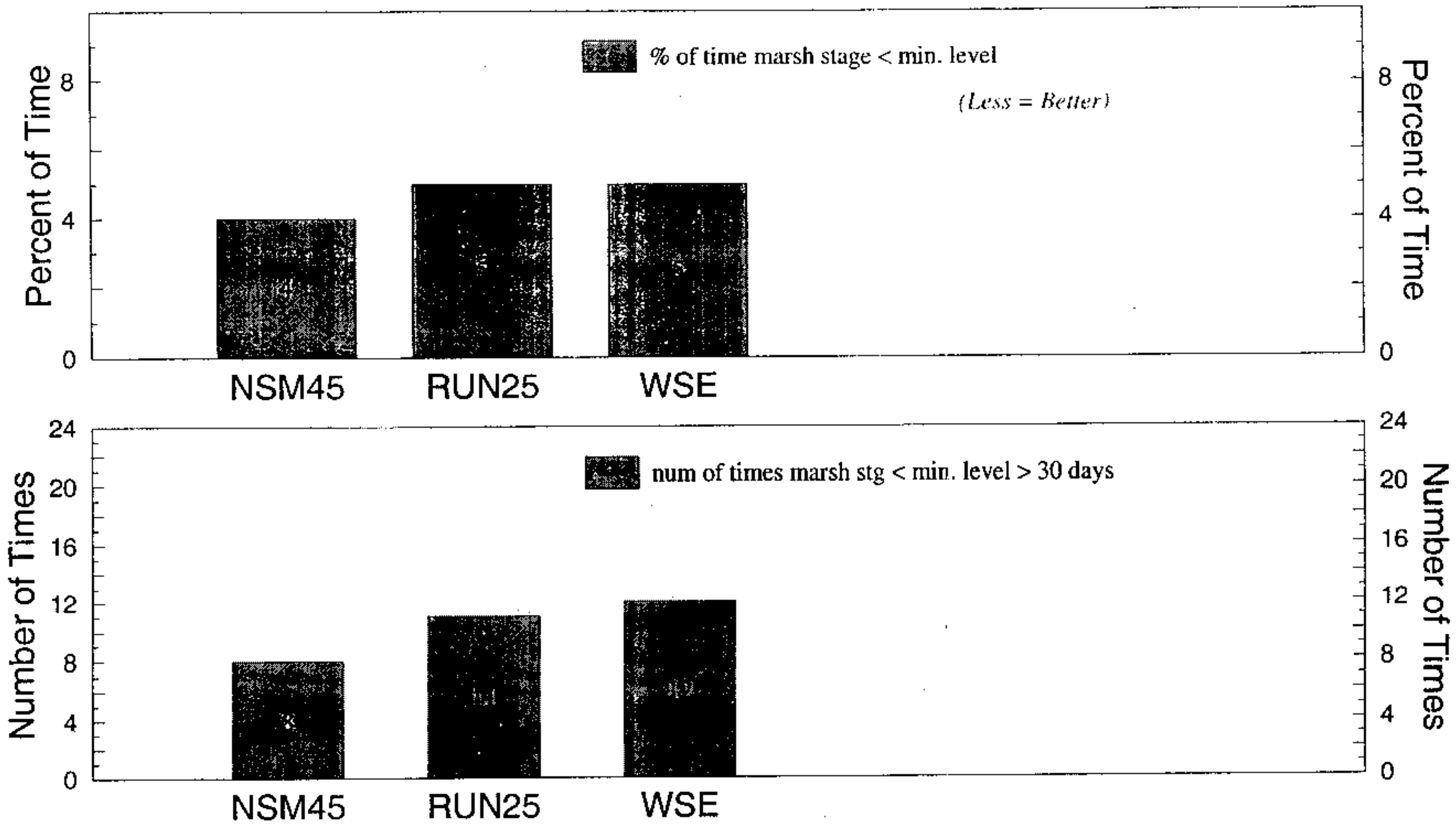
Normalized Stage Duration Curves at Cell (R24 C25)
South End of WCA–3B



Note: Normalized stage is stage referenced to Land Elevation. Thus, values above zero indicates ponding while below zero indicates depth to the water table.

Run date: 12/10/98 03:22:57
For Planning Purposes Only
SFWMM V3.6P

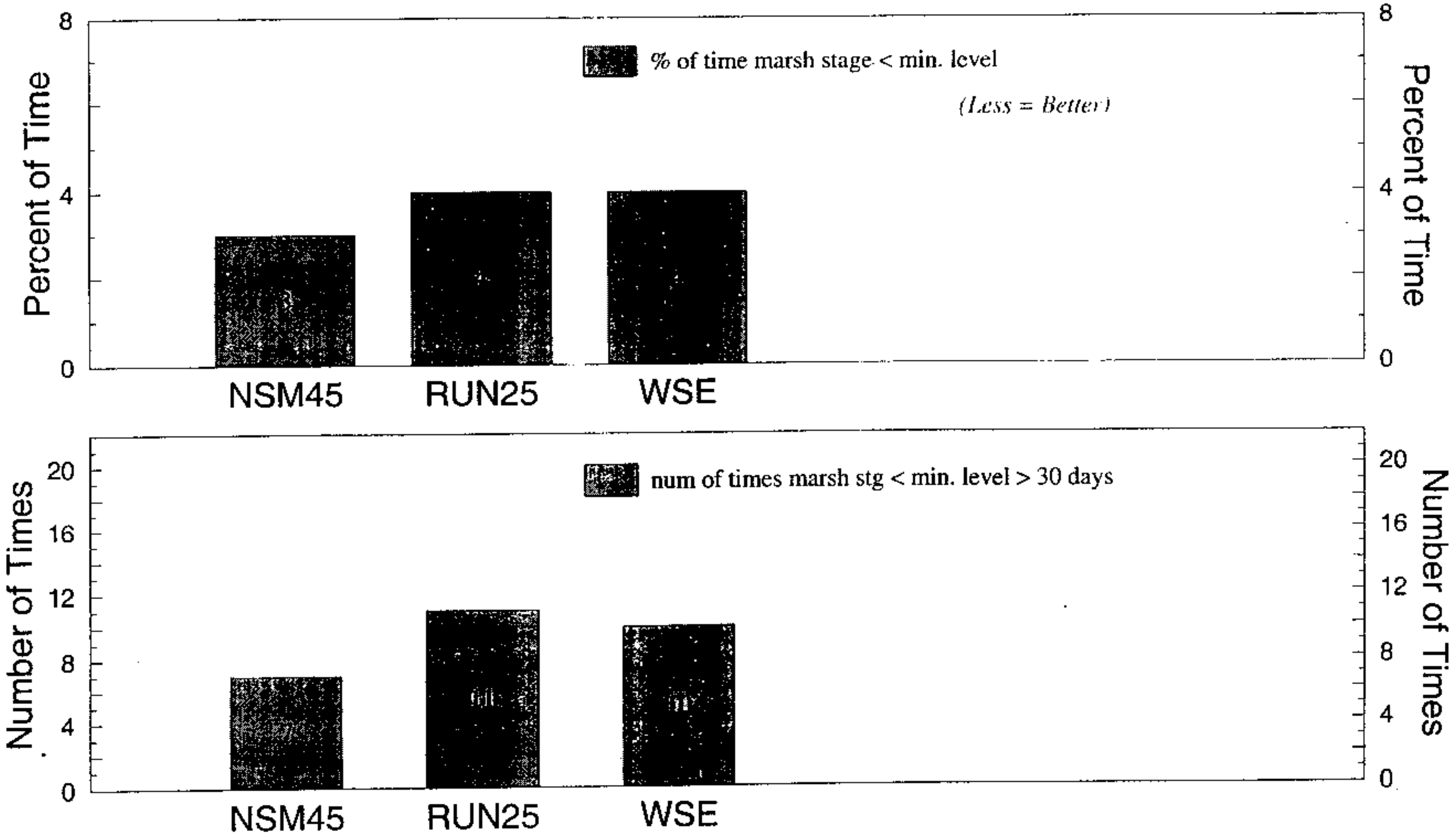
% of Time Marsh Stage < Minimum Level Criteria and Occurrences* > 30 days (2A–17, Cell R40 C29, Proposed Min Lvl 1 ft below ground)



*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 12/10/98 05:13:18
For Planning Purposes Only
SFWMM V3.6P

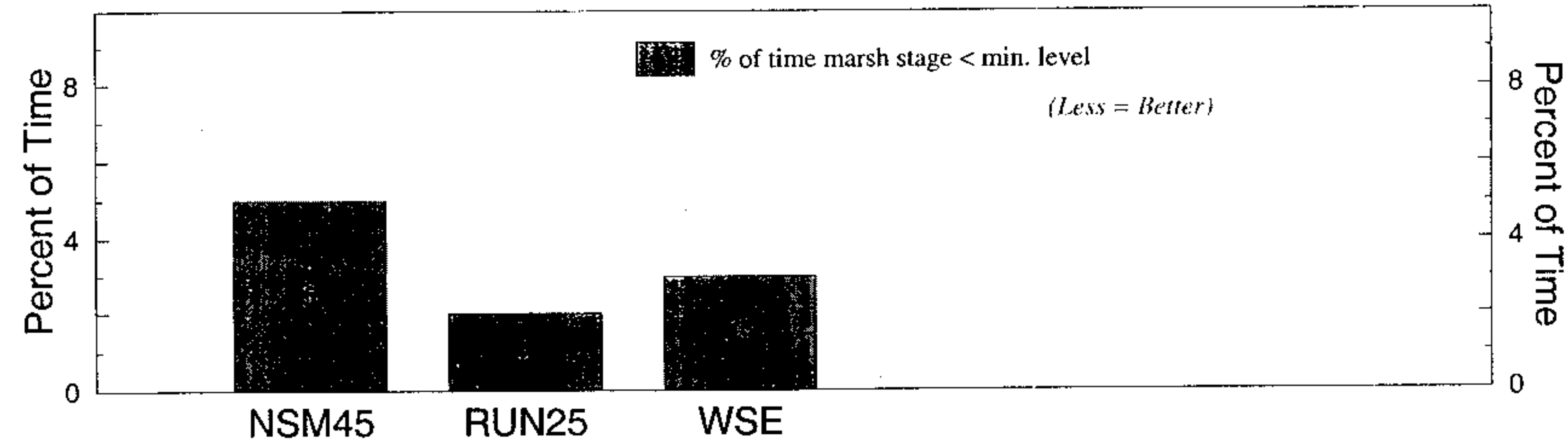
% of Time Marsh Stage < Minimum Level Criteria and Occurrences* > 30 days (3A–2, Cell R36 C18, Proposed Min Lvl 1 ft below ground)

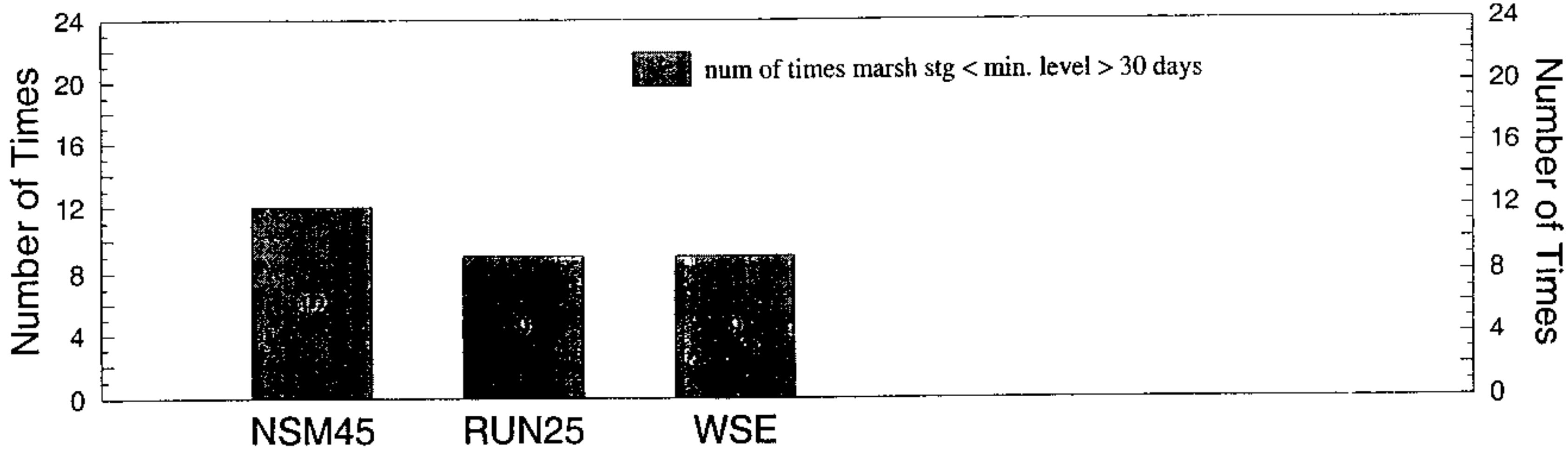


*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 12/10/98 05:14:32
For Planning Purposes Only
SFWMM V3.6P

% of Time Marsh Stage < Minimum Level Criteria and Occurrences* > 30 days
(3A–3, Cell R37 C25, Proposed Min Lvl 1 ft below ground)

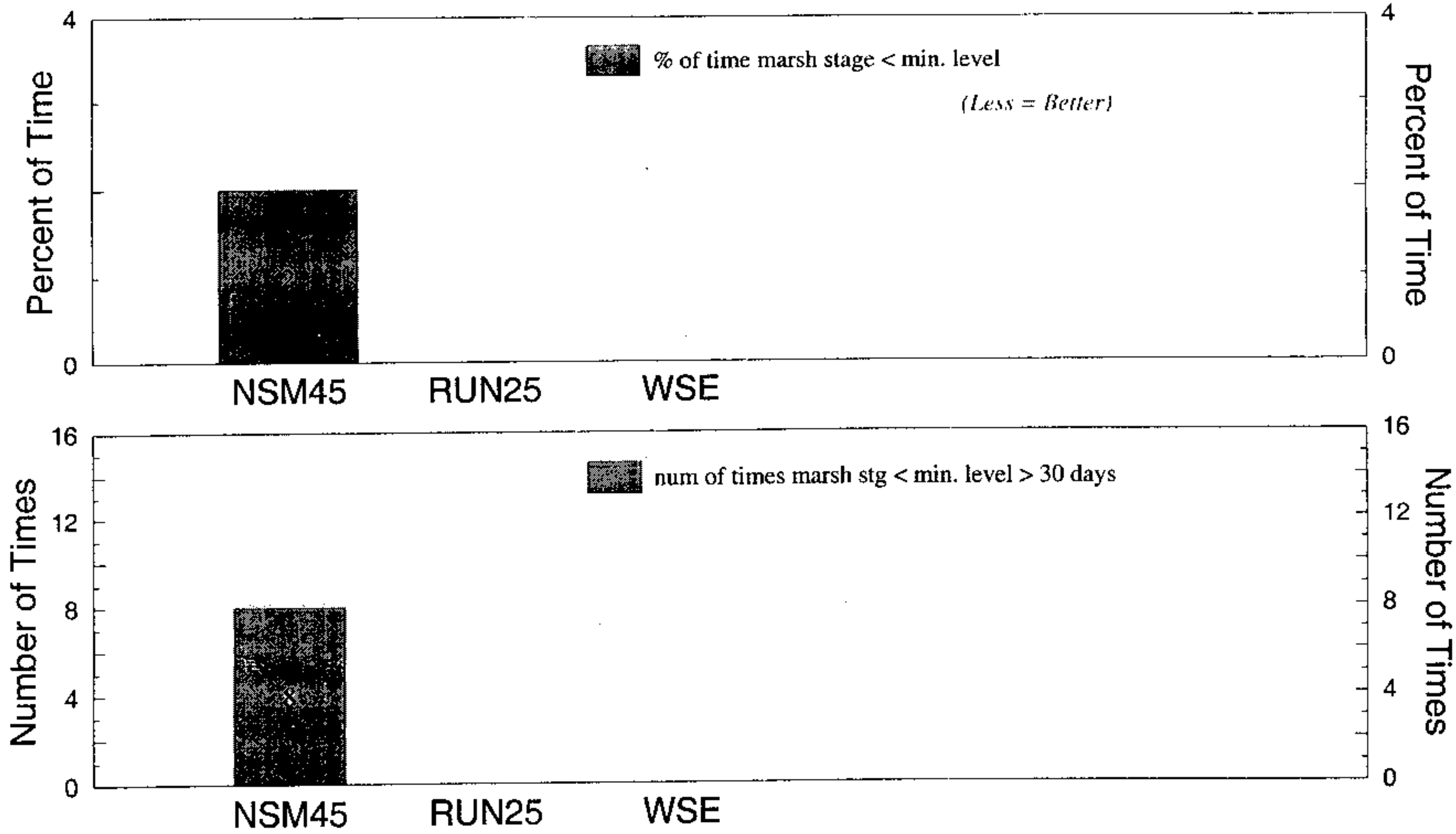




*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 12/10/98 05:08:34
For Planning Purposes Only
SFWMM V3.6P

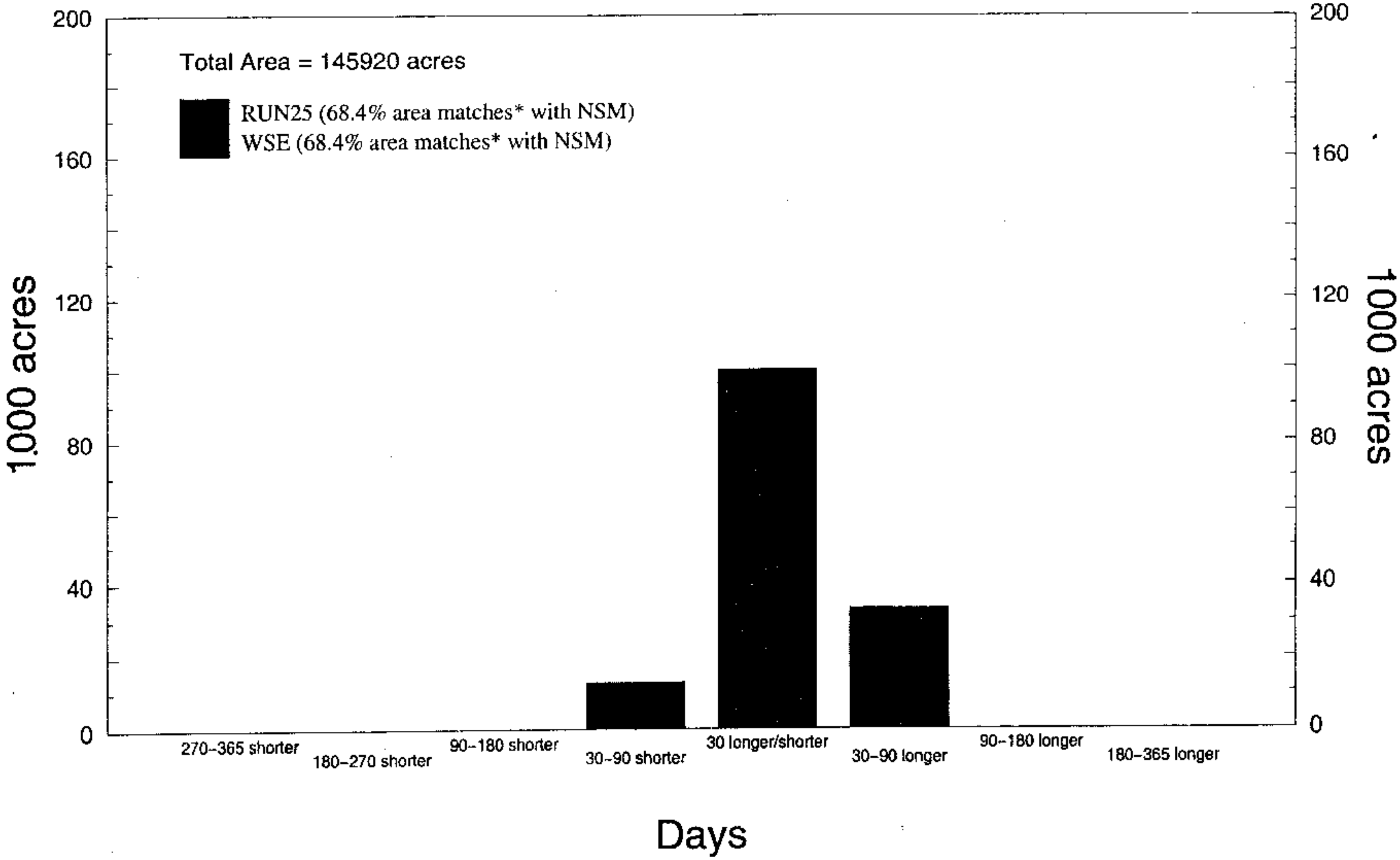
% of Time Marsh Stage < Minimum Level Criteria and Occurrences* > 30 days
(Gage 3A–28, Cell R24 C19, Proposed Min Lvl 1 ft below ground)



*Note: The bottom bars display the number of occurences that the marsh stage falls below ground for longer than 30days with the additional condition that the stage falls below the minimum level at least one day during the 30day interval.

Run date: 12/10/98 04:43:10
For Planning Purposes Only
SFWMM V3.6P

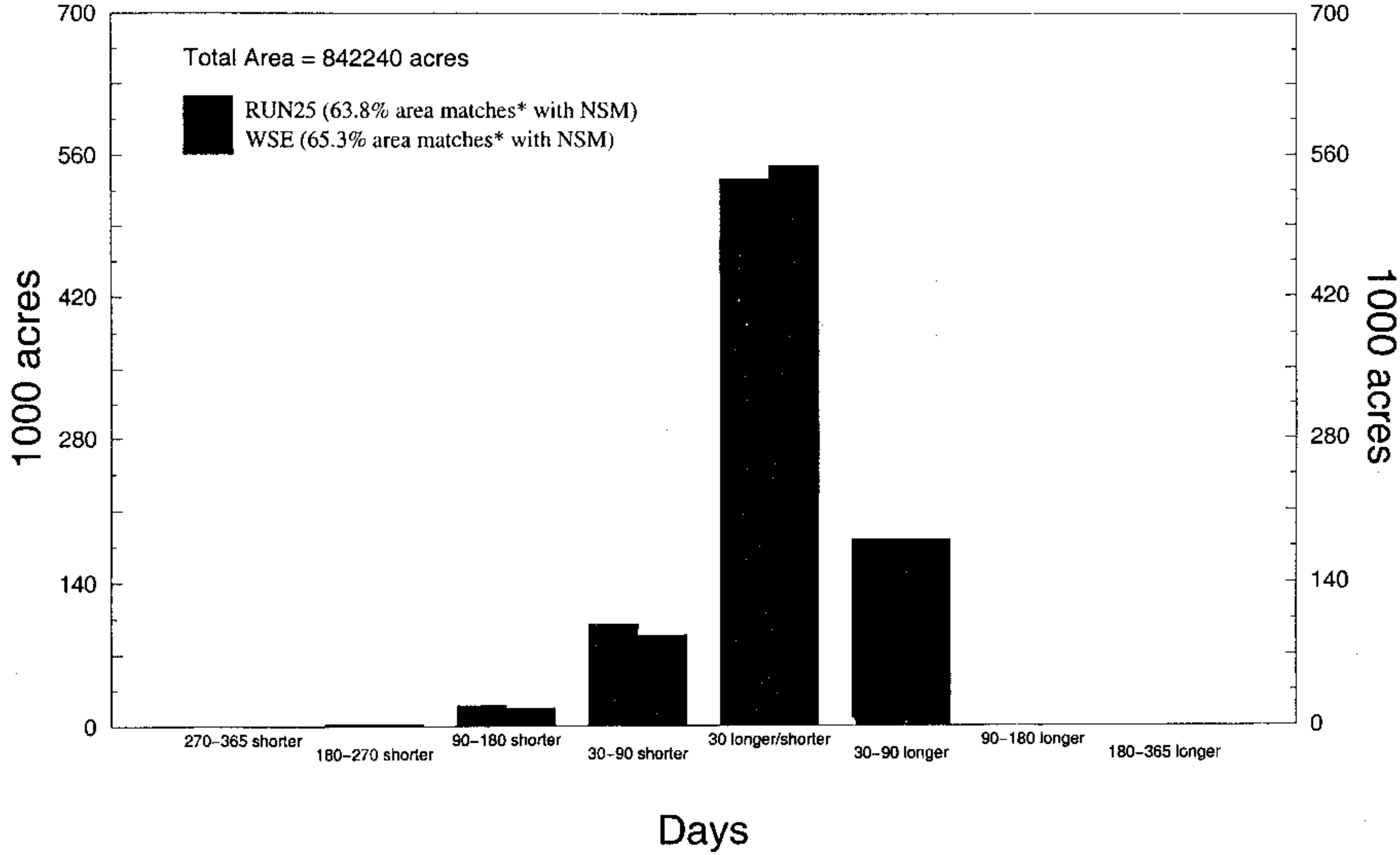
Mean NSM hydroperiod matches for WCA-1 for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 12/10/98 02:02:59
For Planning Purposes Only
SFWMM V3.6P

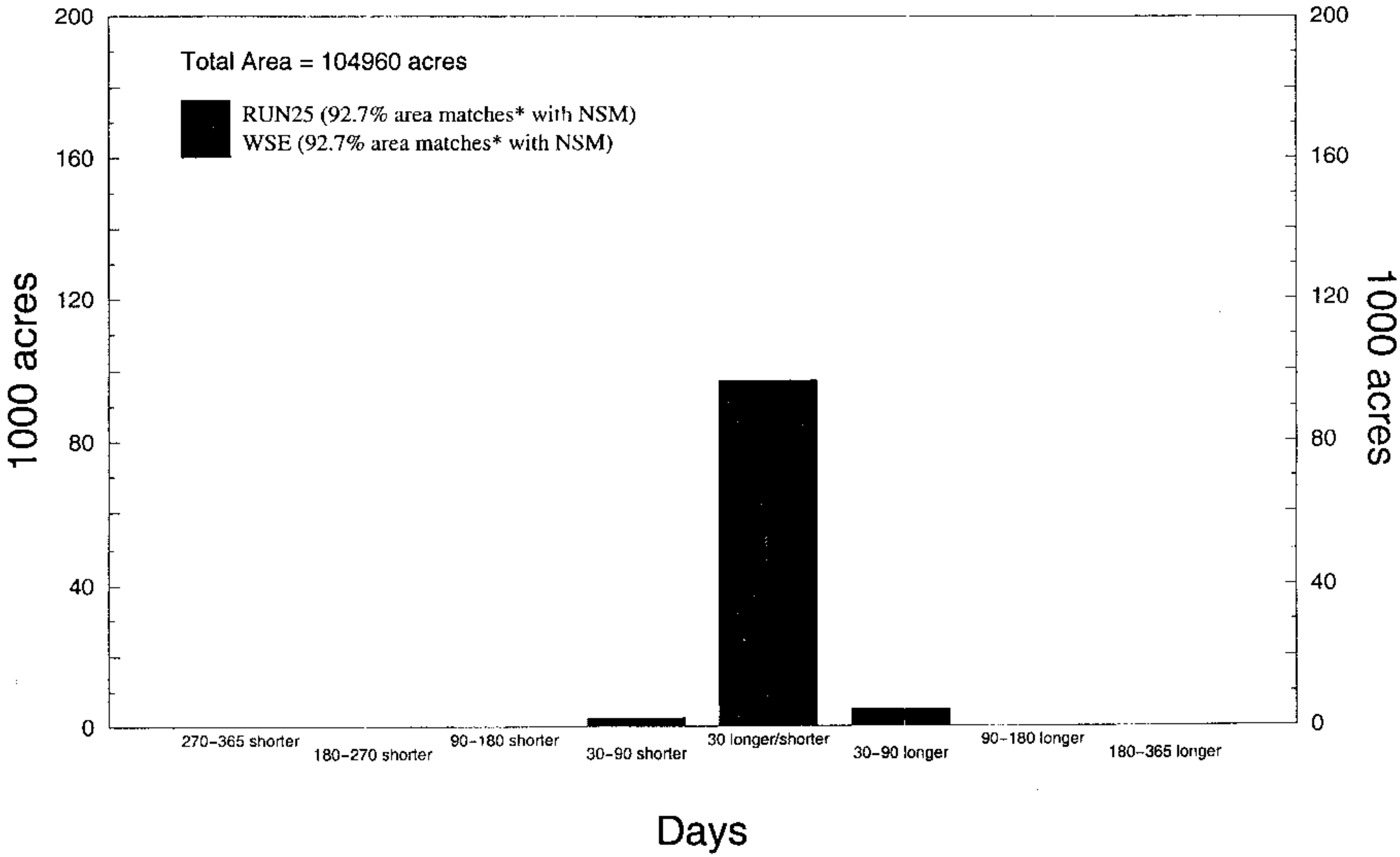
Mean NSM hydroperiod matches for the WCA SYSTEM for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 12/10/98 02:04:24
For Planning Purposes Only
SFWMM V3.6P

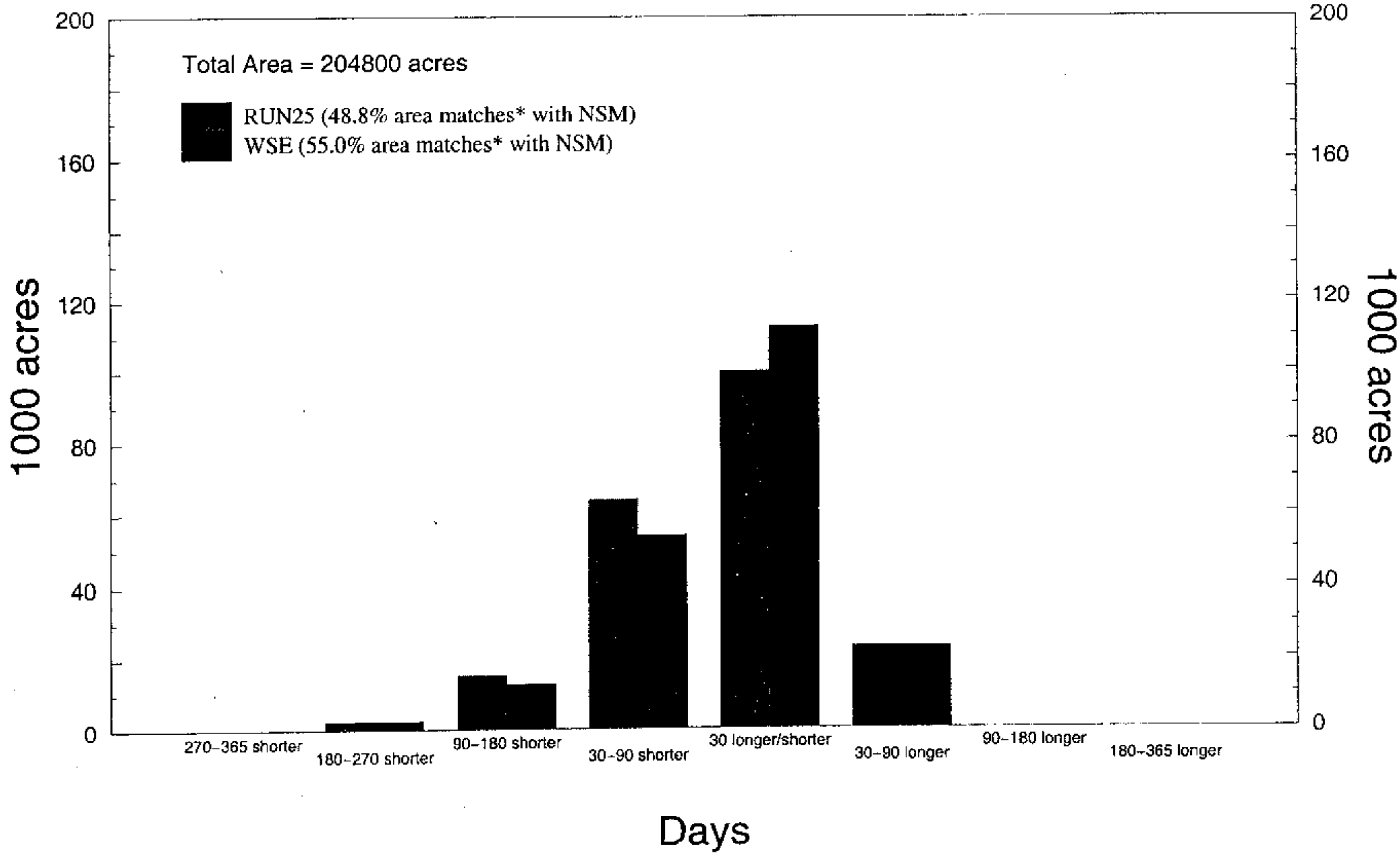
Mean NSM hydroperiod matches for
WCA-2A for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 12/10/98 02:03:12
For Planning Purposes Only
SFWMM V3.6P

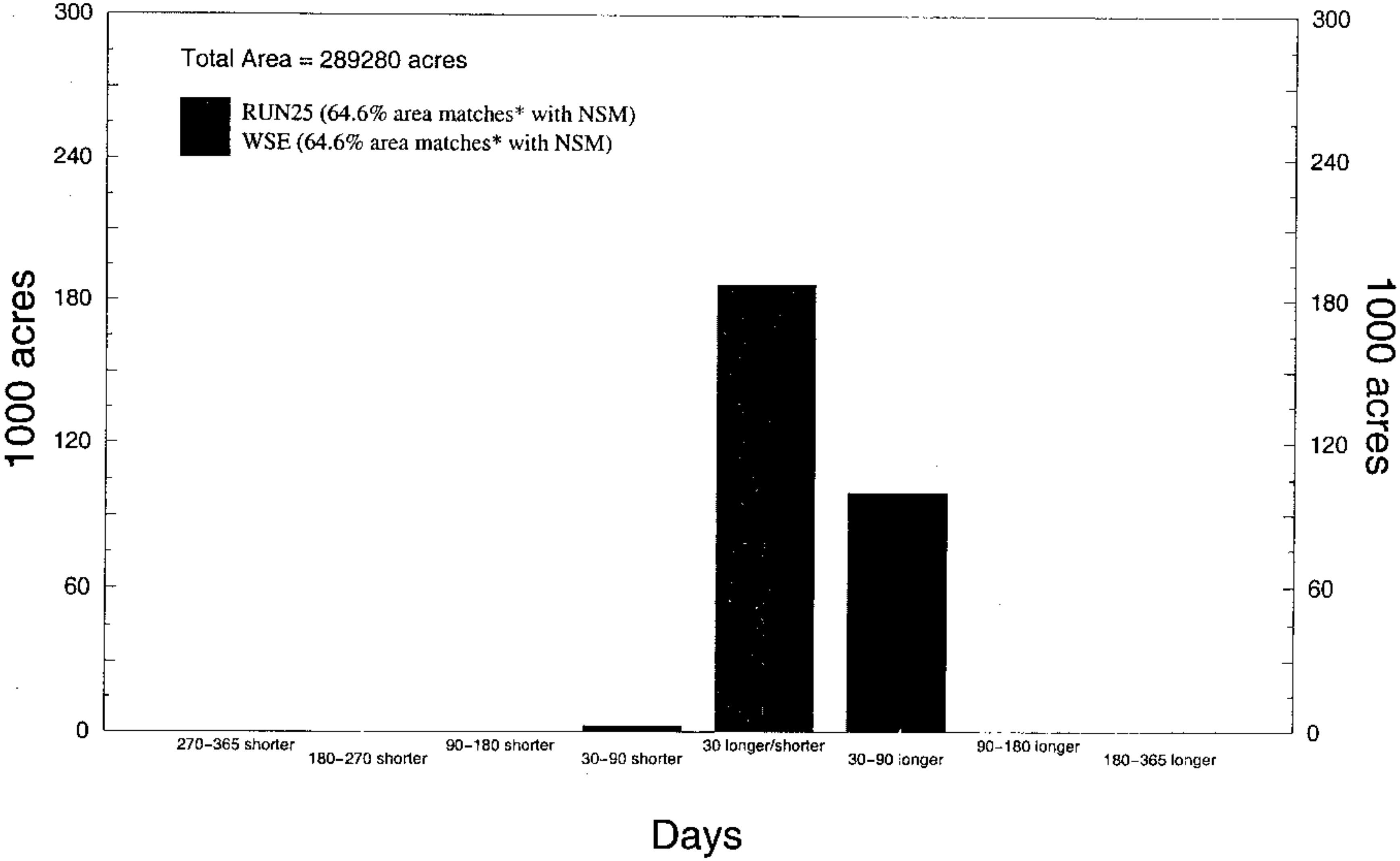
Mean NSM hydroperiod matches for WCA-3A(North) for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 12/10/98 02:03:35
For Planning Purposes Only
SFWMM V3.6P

Mean NSM hydroperiod matches for WCA-3A(South) for the 31 yr. simulation

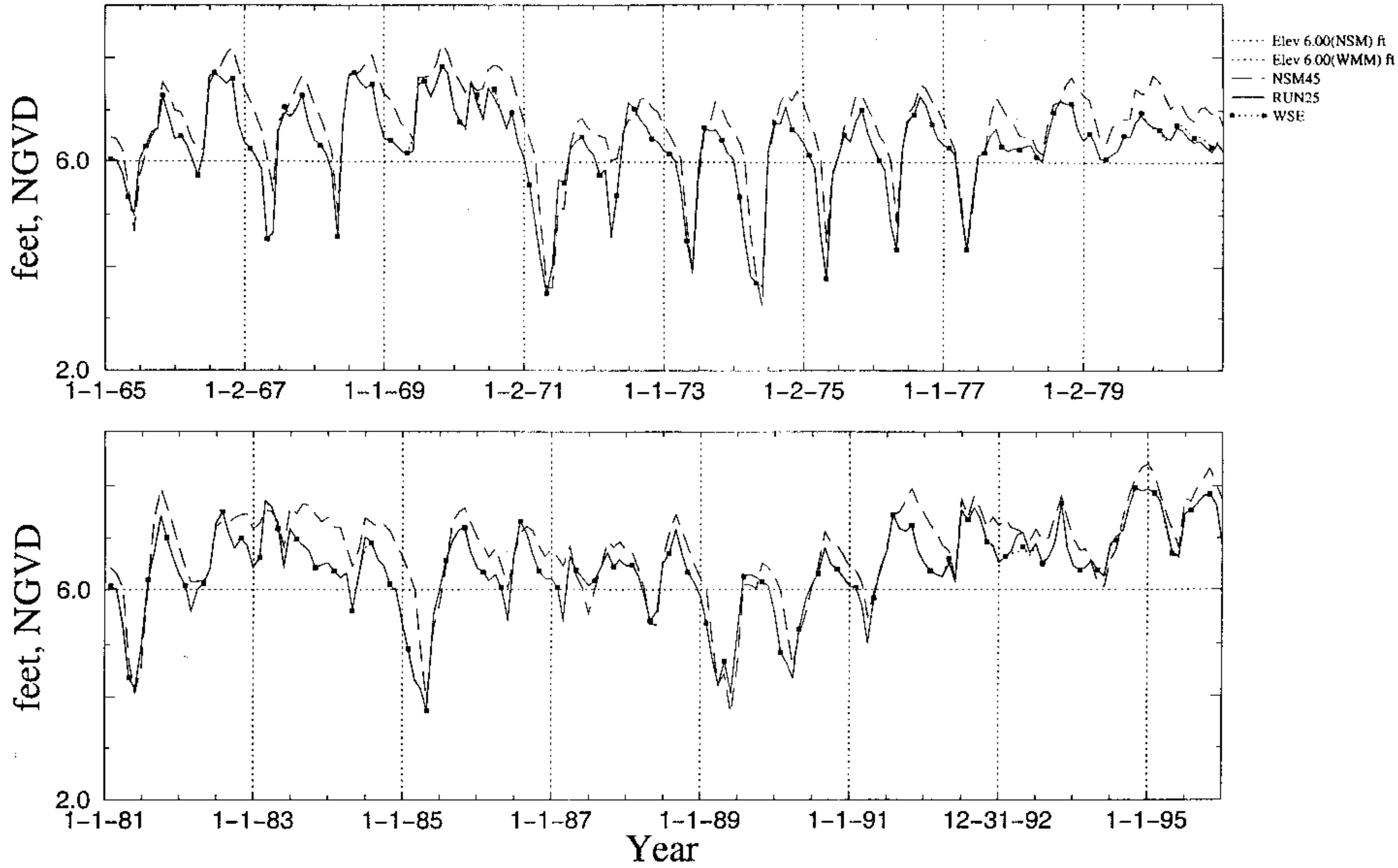


Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 12/10/98 02:03:48
For Planning Purposes Only
SFWMM V3.6P

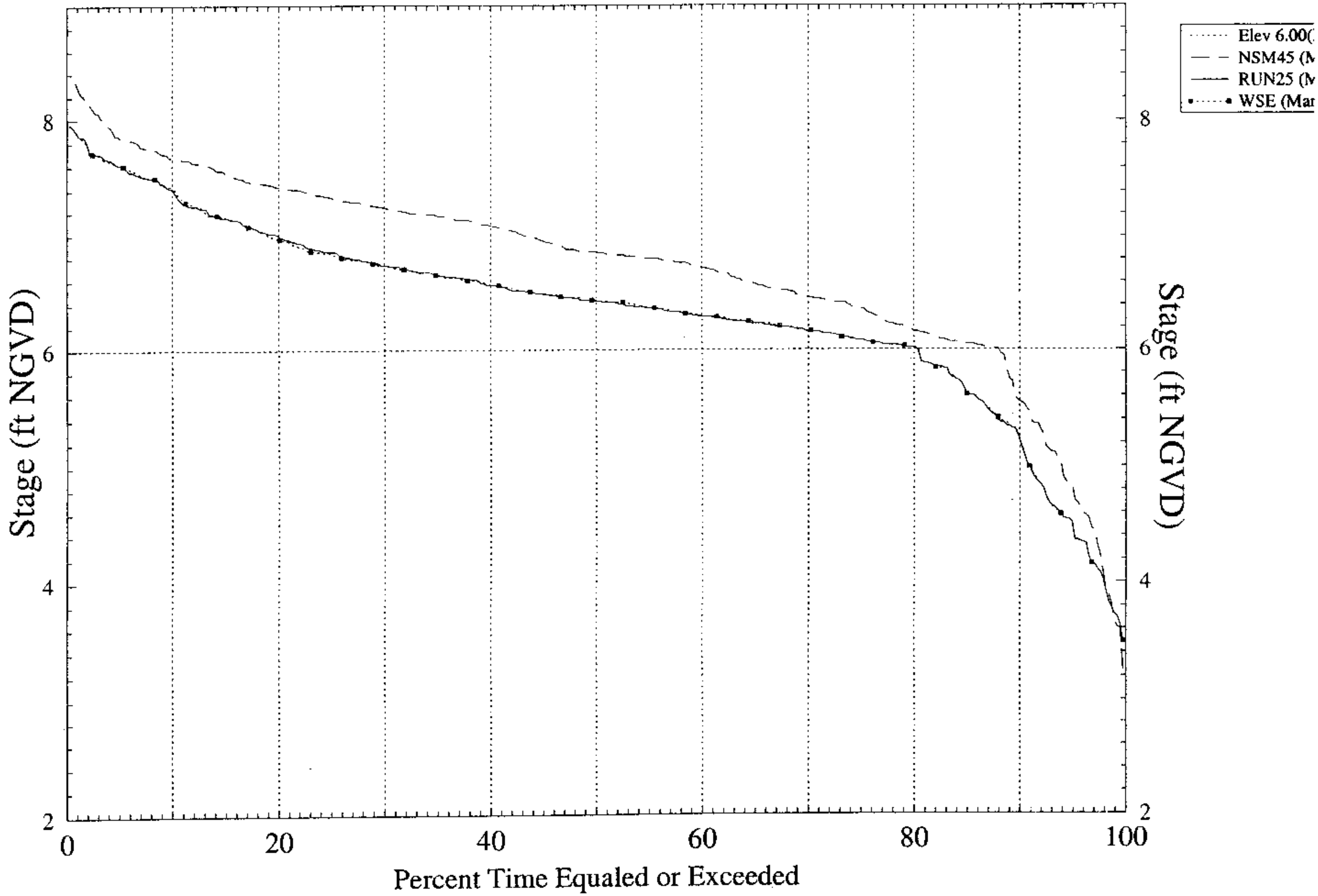
Performance Measures for
Everglades National Park

Stage Hydrograph at NW SRS
Gage G−620, Cell R19 C18



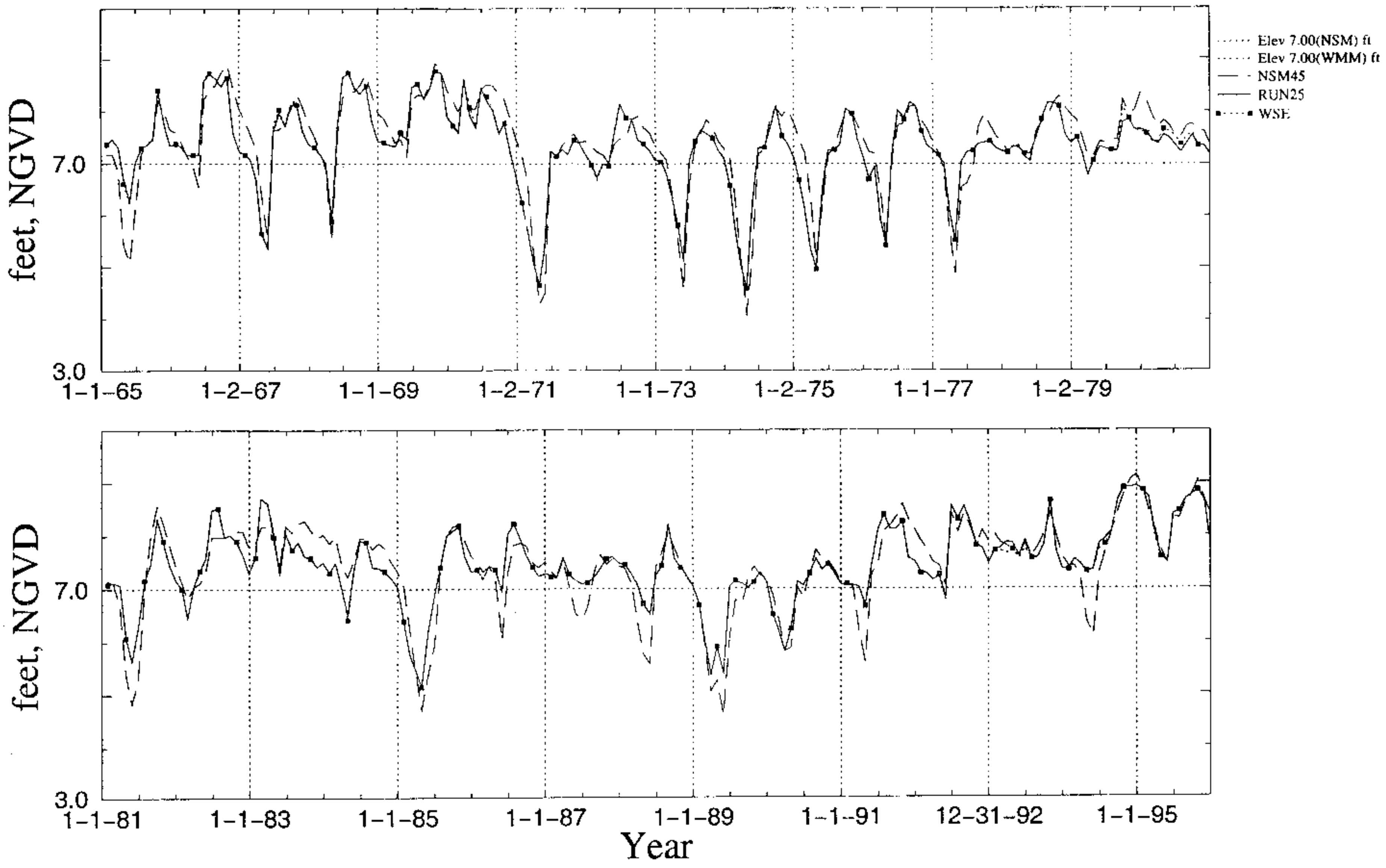
Run date: 12/10/98 02:57:52
For Planning Purposes Only
SFWMM V3.6P

Stage Duration Curves at NW SRS
Gage G–620, Cell R19 C18



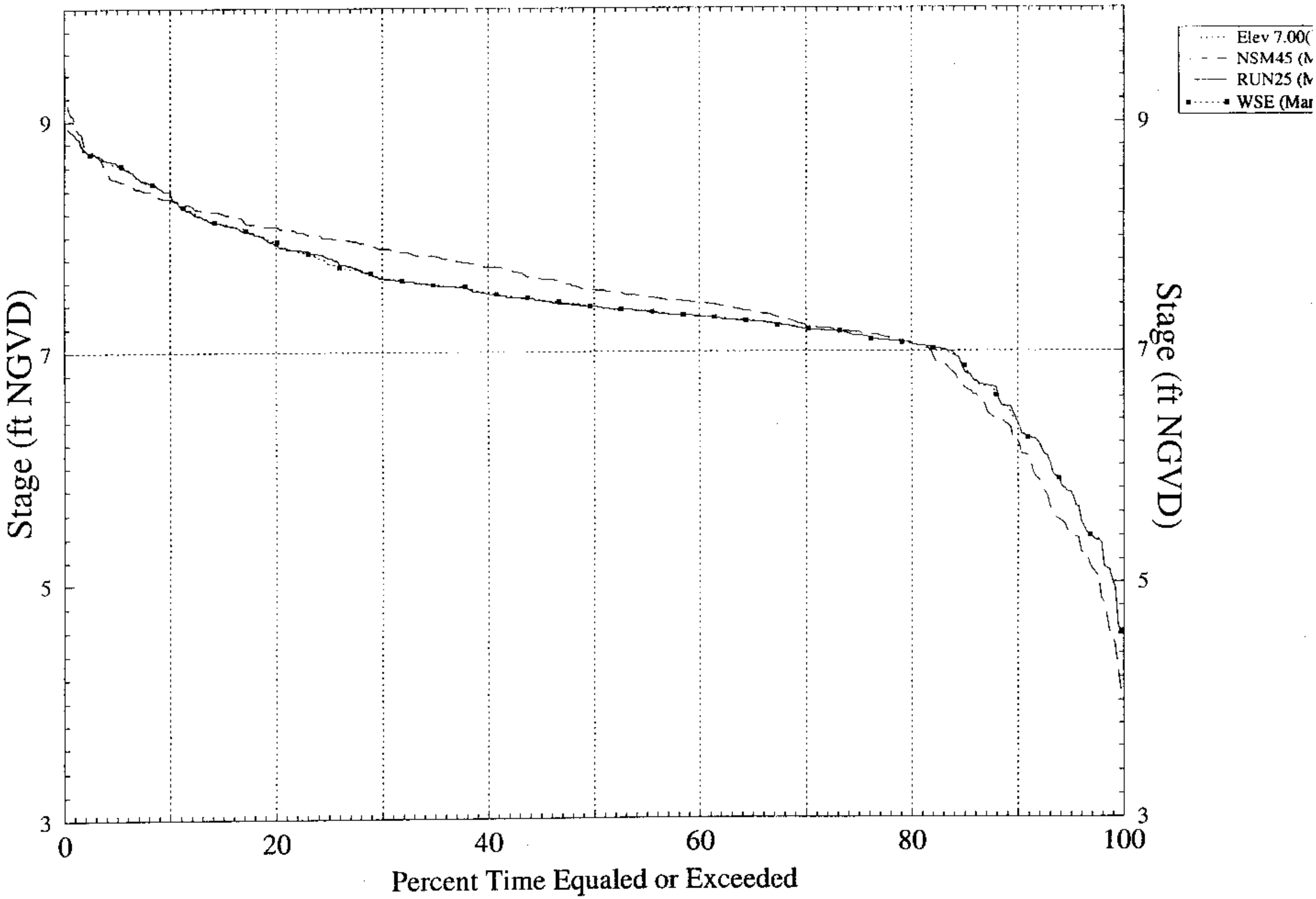
Run date: 12/10/98 02:57:43
For Planning Purposes Only
SFWMM V3.6P

Stage Hydrograph at Northern Shark River Slough
Gage NP_201, Cell R21 C19



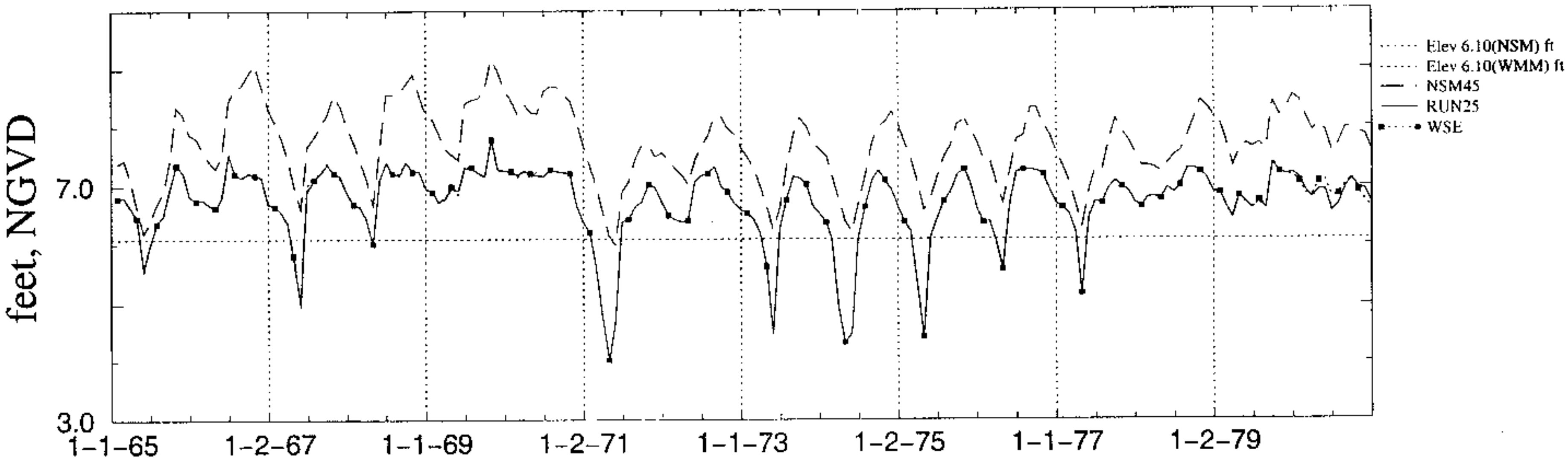
Run date: 12/10/98 02:52:29
For Planning Purposes Only
SFWMM V3.6P

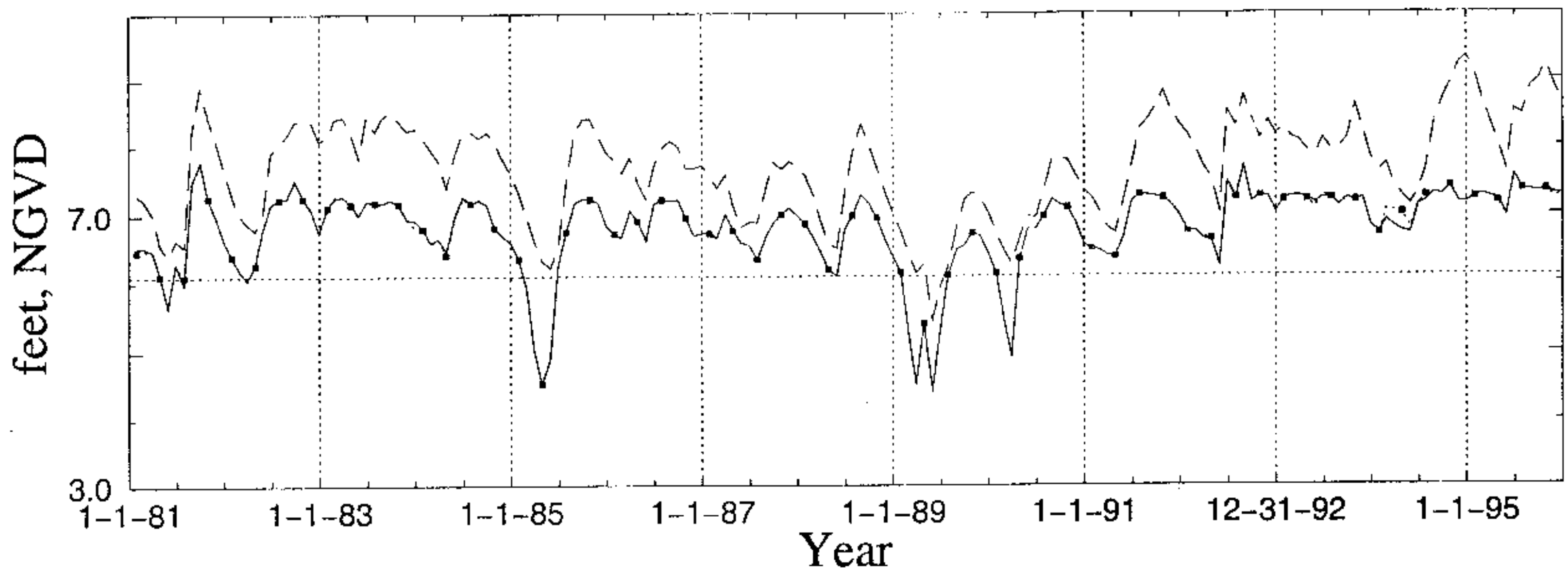
Stage Duration Curves at Northern Shark River Slough
Gage NP_201, Cell R21 C19



Run date: 12/10/98 02:52:21
For Planning Purposes Only
SFWMM V3.6P

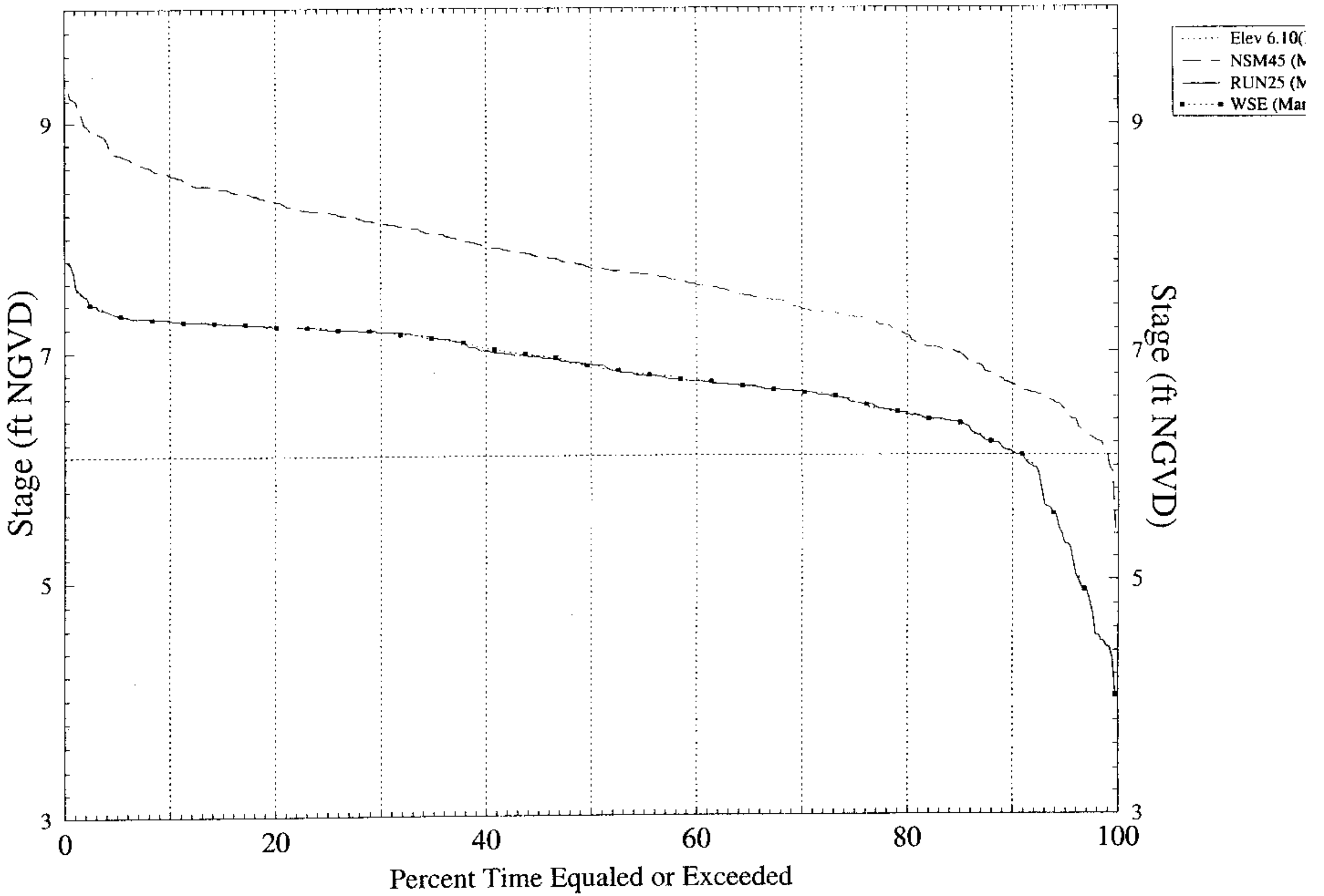
Stage Hydrograph at N.E. Shark River Slough
Gage NESRS_2, Cell R21 C24





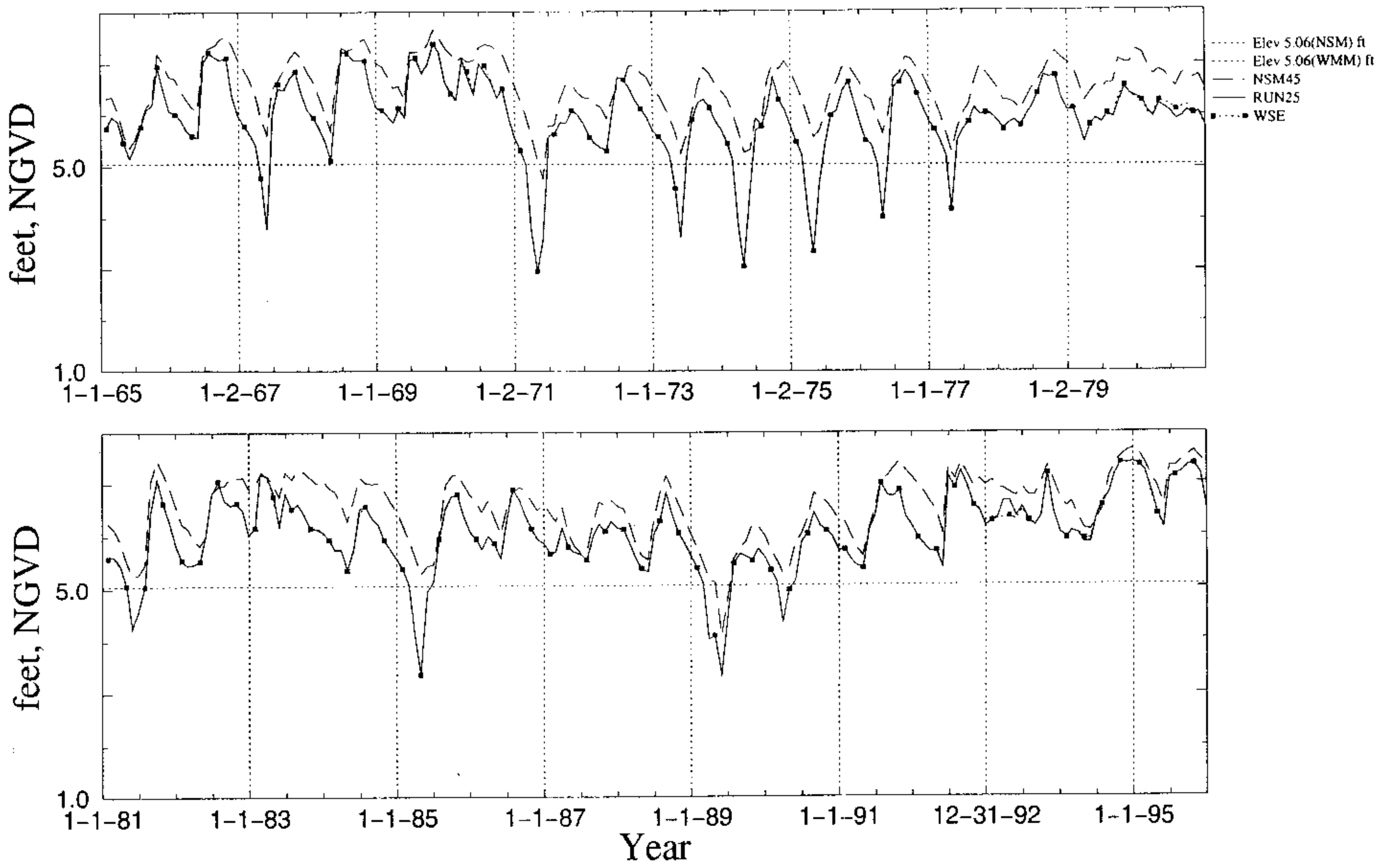
Run date: 12/10/98 02:53:02
For Planning Purposes Only
SFWMM V3.6P

Stage Duration Curves at N.E. Shark River Slough
Gage NESRS_2, Cell R21 C24



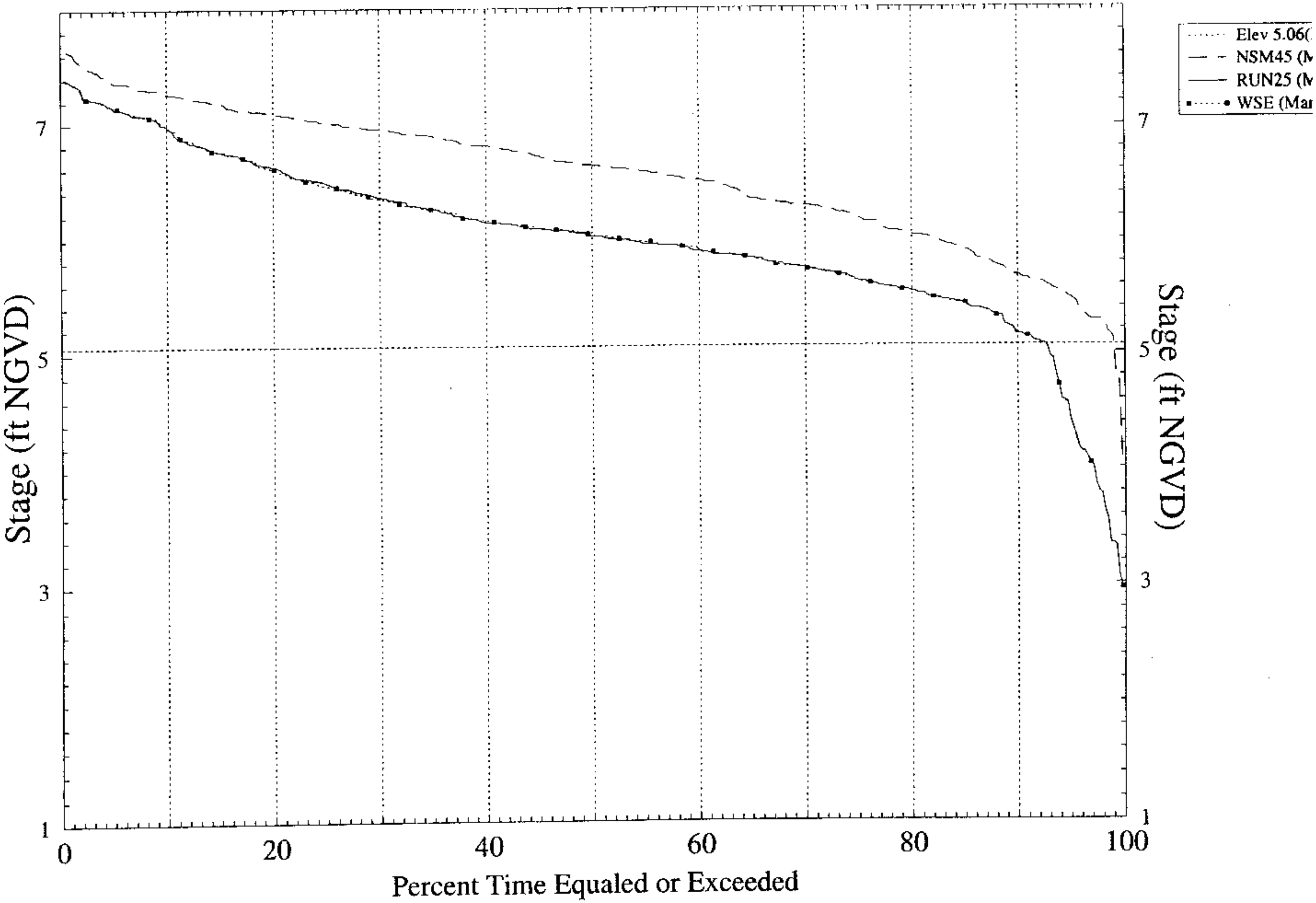
Run date: 12/10/98 02:52:54
For Planning Purposes Only
SFWMM V3.6P

Stage Hydrograph at Everglades National Park
Gage NP_33, Cell R17 C20



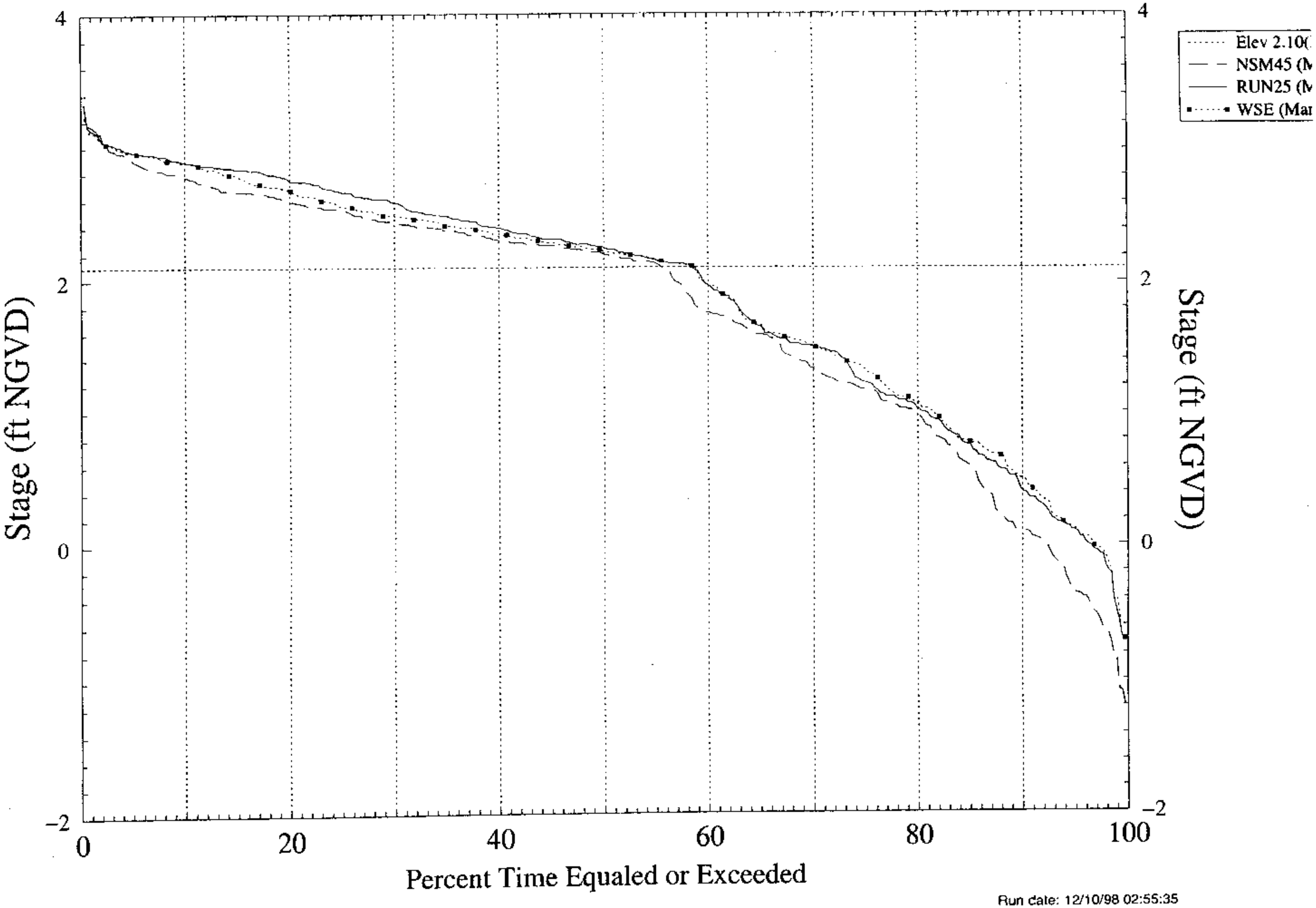
Run date: 12/10/98 02:54:40
For Planning Purposes Only
SFWMM V3.6P

Stage Duration Curves at Everglades National Park
Gage NP_33, Cell R17 C20



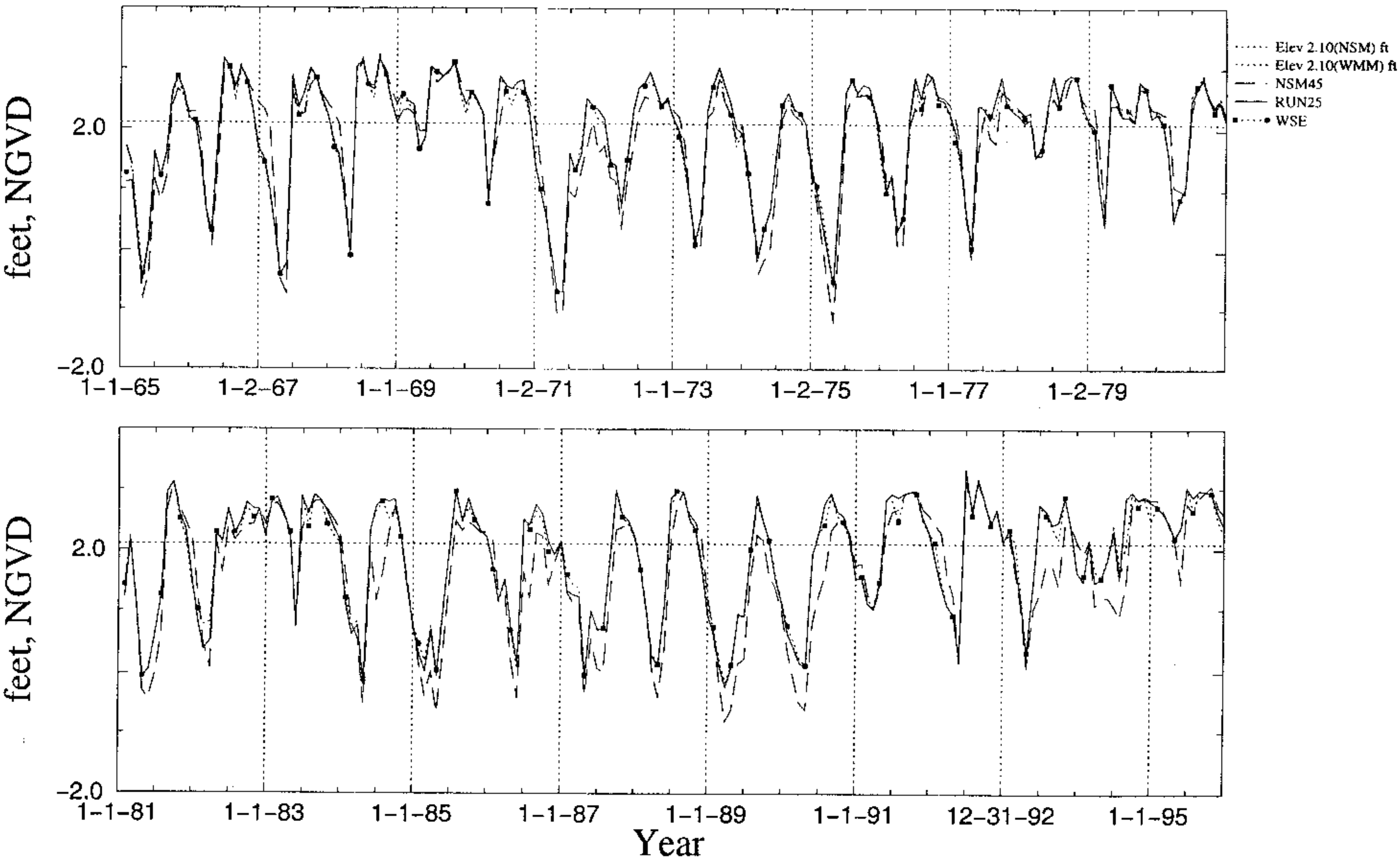
Run date: 12/10/98 02:54:32
For Planning Purposes Only
SFWMM V3.6P

Stage Duration Curves at C–111 Basin
Gage C111_G1251, Cell R7 C24



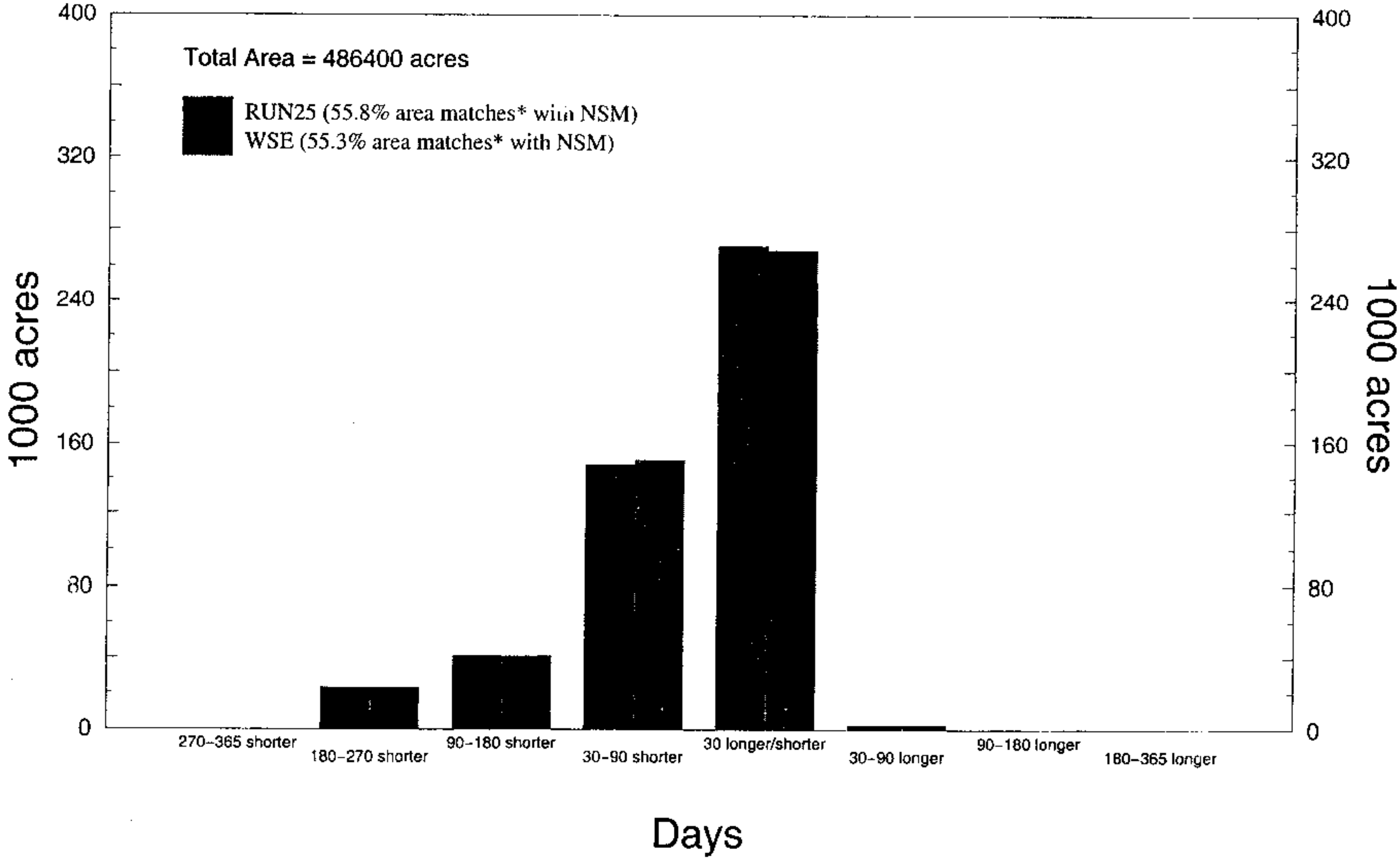
Run date: 12/10/98 02:55:35
For Planning Purposes Only
SFWMM V3.6P

Stage Hydrograph at C-111 Basin
Gage C111_G1251, Cell R7 C24



Run date: 12/10/98 02:55:43
For Planning Purposes Only
SFWMM V3.6P

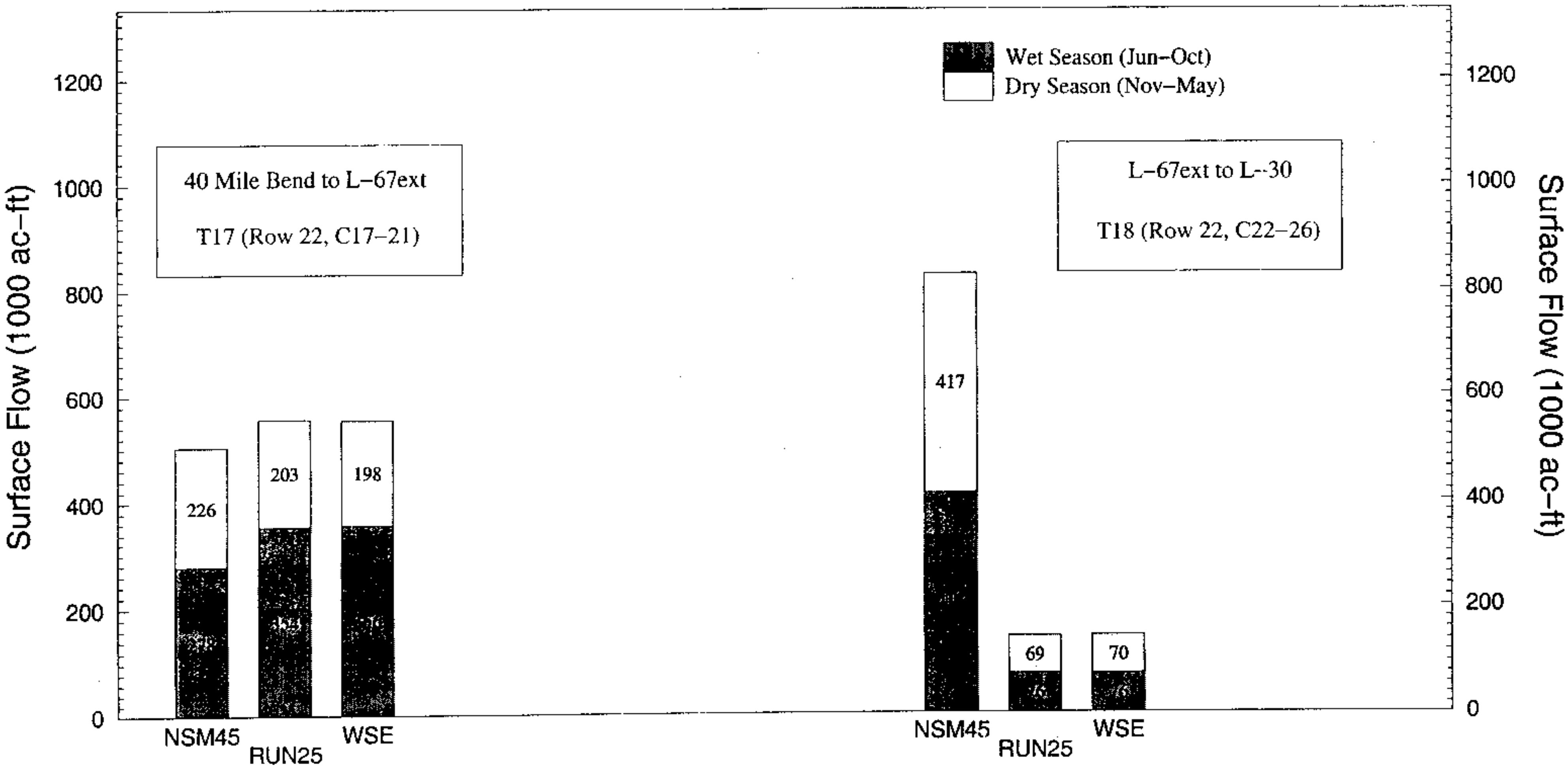
Mean NSM hydroperiod matches for the Everglades National Park for the 31 yr. simulation



Note: xaxis represents hydroperiod days shorter or longer as compared to NSM
*Match corresponds to 30 hydroperiod days shorter or longer than NSM.

Run date: 12/10/98 02:04:11
For Planning Purposes Only
SFWMM V3.6P

Average Annual Overland to ENP South of Tamiami Trail, West & East of L–67ext for the 31 year simulation period



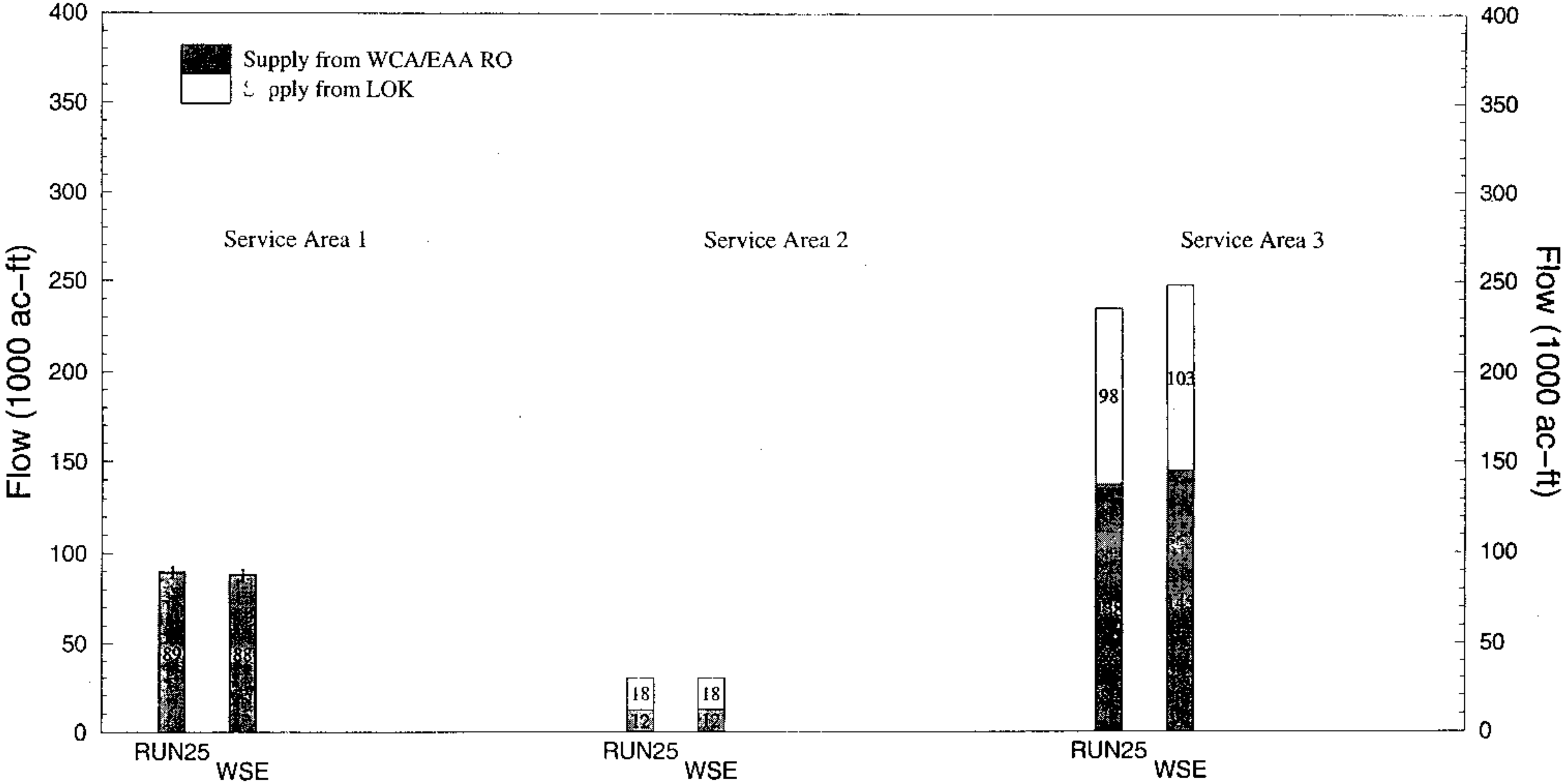
Note: Flow represents overland flows for cells Row 22 Columns 22 thru 26. NSM water depths at key ENP gage locations are used as operational targets for most alternatives. NSM flows are NOT targets (except for ALT #4) and are shown for comparative purposes only.

Run date: 12/10/98 03:53:33
For Planning Purposes Only
SFWMM V3.6P

Performance Measures for the

Lower East Coast Service Areas

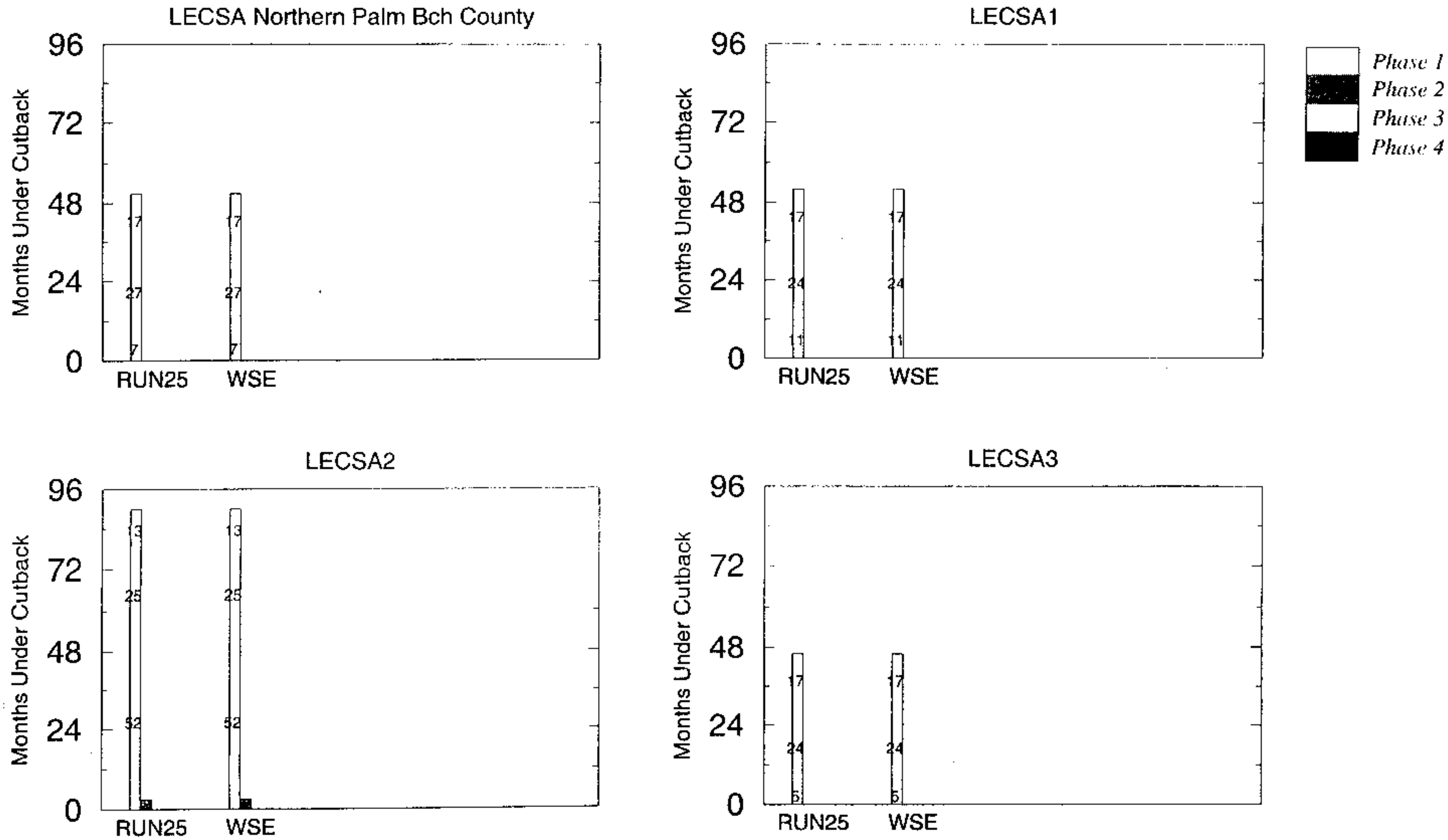
Mean Annual Regional System Water Supply Deliveries to LEC Service Areas for the five Drought years (71,75,81,85,89)



Note: Structure flows included: SA1=S39+LWDD+ADDSLW+ACMEWS+WSL8S+HLFASR+C51FAS+WSC1+S1ATHL+CPBRWS+BPRL8S
SA2=S38+S34+NNRFAS; SA3=S31+S334+S337+BRDRWS+LBTC6+LBTDBL+LBTL30+LBTSC+LBTC9+LBTC2+C9RWS
Supply RECEIVED from LOK may be less than what is DELIVERED at LOK due to conveyance constraints.
Regional System is comprised of LOK and WCAs.

Run date: 12/10/98 01:11:50
For Planning Purposes Only
SFWMM V3.6P

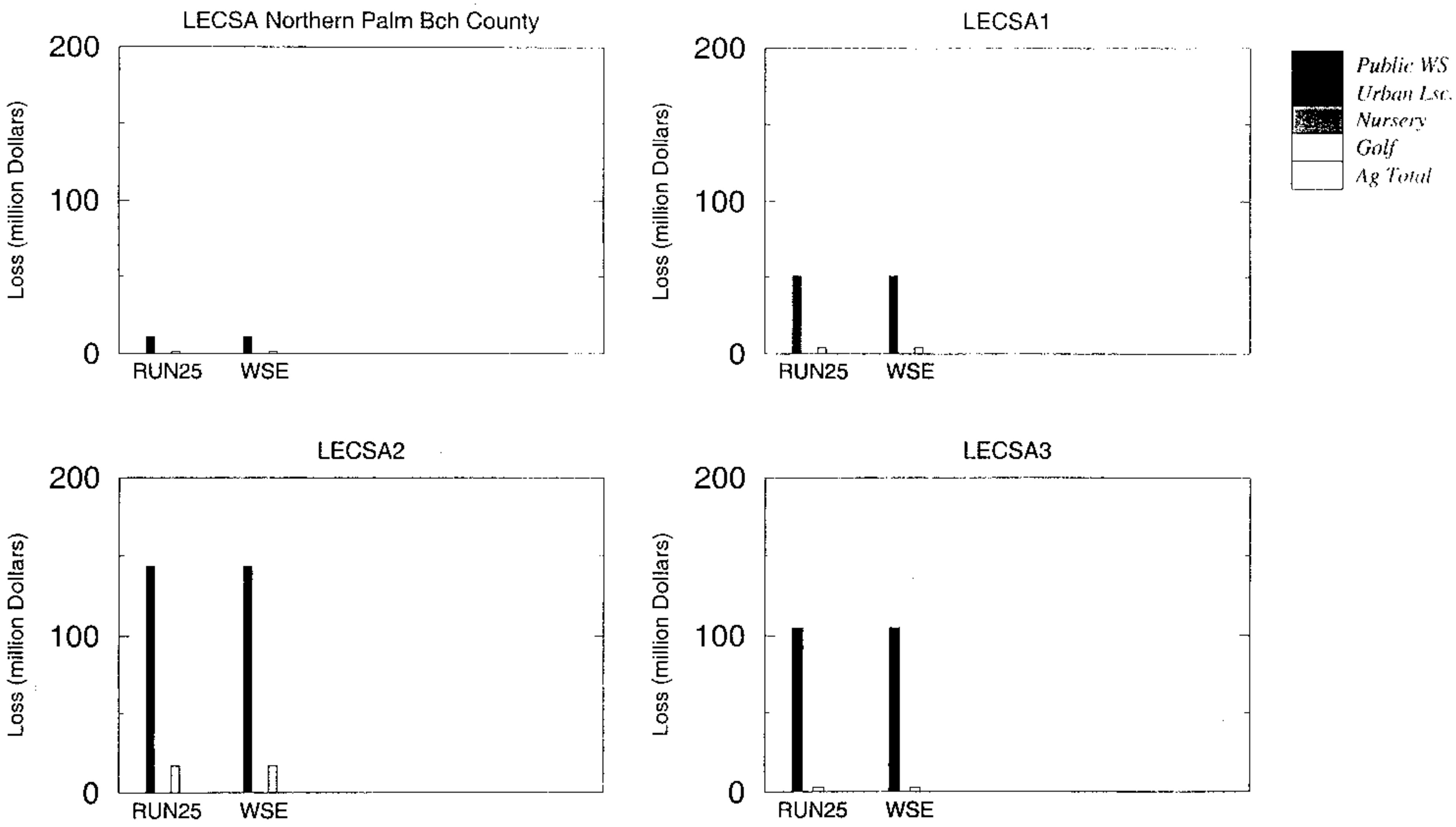
Number of Months of Simulated Water Supply Cutbacks
for the 1965 – 1995 Simulation Period



Note: Phase 1 water restrictions could be induced by a) Lake stage in Supply Side Management Zone (indicated by upper data label), b) Local Trigger well stages (lower data label), and c) Dry season criteria (indicated by middle data label).

Run date: 12/10/98 01:12:36
For Planning Purposes Only
SFWMM V3.6P

Total Water Shortage Impacts (Losses) for the 31 year Simulation Period



Run date: 12/10/98 02:23:19
For Planning Purposes Only
SFWMM V3.6P